

Hypocenter distribution and heterogeneous seismic velocity structure in and around the focal area of the 2008 Iwate-Miyagi Nairiku Earthquake, NE Japan—Possible seismological evidence for a fluid driven compressional inversion earthquake

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We have done seismic tomography in and around the focal area of the 2008 Iwate-Miyagi Nairiku Earthquake (M 7.2) occurred on June 14, 2008 in NE Japan. We used data from temporary aftershock observation network deployed just after the occurrence of the present earthquake. Based on the distribution of aftershocks, the fault plane of the mainshock is inferred to dip to the west. Small immediate foreshocks and preceding seismic activity in 1999–2000 on the fault plane in the vicinity of the hypocenter of the mainshock of this earthquake were observed. Lower-seismic-velocity hanging wall can be imaged in the central and the northern part of the focal area. This possibly suggests the present earthquake is a compressional inversion earthquake. The low-velocity zone in the lower crust extends upward to the upper crust, branches into three portions and reaches each active volcano. This low-velocity region can be seen just beneath the mainshock hypocenter and the whole focal area, suggesting that crustal fluid possibly promote the occurrence of the 2008 earthquake.

Key words: Seismic velocity structure, aftershock, foreshock, inversion tectonics, crustal fluid.

1. Introduction

A large shallow earthquake (named the 2008 Iwate-Miyagi Nairiku Earthquake) with a Japan Meteorological Agency (JMA) magnitude of 7.2 occurred in the central part of NE Japan on June 14, 2008. Focal area of the present earthquake is located in the Tohoku backbone range strain concentration zone (Miura *et al.*, 2002) along the volcanic front. The focal mechanism or moment tensor shows reverse-type focal mechanism (cf. United States Geological Survey (USGS) MOMENT TENSOR (http://neic.usgs.gov/neis/eq_depot/2008/eq_080613_tfdp/neic_tfdp_fmt.html), National Institute for Earth Science and Disaster Prevention (NIED) MOMENT TENSOR (<http://www.fnet.bosai.go.jp/event/tdmt.php?ID=20080613234200&all=&v=&LANG=en&?LANG=en>)).

The compressional inversion tectonics is dominated in NE Japan at present (e.g. Sato *et al.*, 2002; Sibson, 2009). In Miocene when Japan-sea was opened, many normal faults are formed under the extensional stress regime. At present these old normal faults act as reverse fault under the present compressional stress regime. In the case of the 2003 northern Miyagi earthquake (M 6.4), which is about 40 km south from the present earthquake, this compressional inversion

earthquake shows that high-dip angle of fault plane or aftershock alignment and also shows lower velocity hanging wall (Okada *et al.*, 2007a). The plausible cause of the reactivation of such an unfavorably or badly oriented fault is over-pressurized fluid (Sibson, 1990). In the previous paper (Okada *et al.*, 2010), we have found a distinct low-velocity zone in the lower crust just beneath the focal area. These low-velocity zones might correspond to the area with over-pressurized fluid, which is originated from the upwelling flow in the mantle wedge.

Just after the occurrence of this earthquake, Japanese universities (Hokkaido, Hirosaki, Tohoku, Tokyo, Nagoya, Kyoto, Kochi, Kyusyu, Kagoshima) and NIED (National Research Institute for Earth Science and Disaster Prevention) deployed a dense aftershock observation network in and around the focal area (Fig. 1). Total number of temporal stations is 128. Using data from this aftershock observation and other temporary and routinely operated stations, we estimate hypocenter distribution and seismic velocity structure of the crust in and around the whole focal area of the present earthquake in more detail.

2. Data and Method

We determined three-dimensional seismic velocity structure and relocated hypocenters simultaneously using the double-difference tomography method (Zhang and Thurber, 2003).

We adopted two-step procedure. First, we have done

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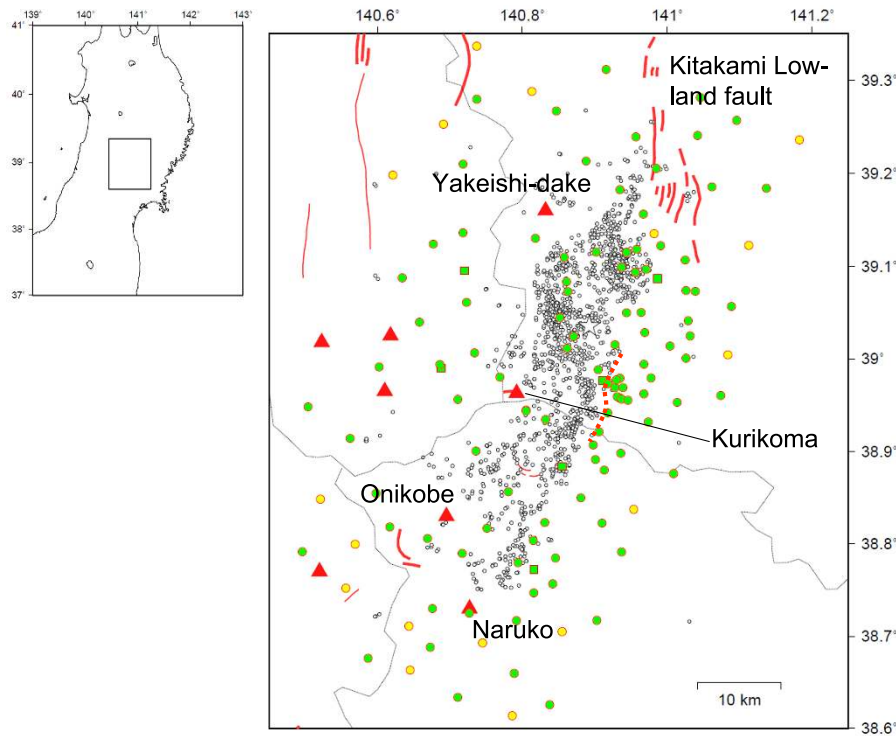


Fig. 1. Distribution of stations deployed by the Group for the aftershock observations of Iwate-Miyagi Nairiku Earthquake in 2008. Green and yellow circles denote the off-line stations deployed in the period from 2008/6 to 2008/10 and from 2008/6 to 2008/8, respectively. Green squares denote the on-line stations deployed in the period from 2008/6 to 2008/10. White open circles denote the aftershocks within 1 week after the mainshock from the Tohoku University automated catalog. Triangles denote volcanoes. Bold lines denote the surface traces of the active faults. Red broken line denotes the approximate location of Mochikorobashi-Hosokura Tectonic Zone (MHTZ). Thin lines indicate the prefecture borders.

regional-scale tomography to obtain rough and deep image in this area (see Okada *et al.*, 2010 for details). We used the shallow seismicity and intermediate depth seismicity in the subducting slab as a data set. Initial velocity structure is Hasegawa *et al.* (1978). Total number of earthquake is about 26000. We used a grid net with intervals of 0.05 degrees in north-south and east-west directions and at depths of 0, 6, 12, 18, 24, 36, 48, 60, 80, 100, 120, and 140 km. The resolution is estimated to be about 10 km to 20 km in whole crust.

Second, we relocate aftershocks and recalculate three-dimensional seismic velocity structure by using dense aftershock observation data. Initial velocity model is the previous one. We used a grid net with an interval of about 3 km in horizontal directions and at depths of 0, 1, 3, 6, 9, 12, 15, 18, 24, 30, 36, 48, 60, 80, 100, 120, and 140 km (Fig. 2). We used 5571 earthquakes (two foreshocks, mainshock, aftershocks and other earthquakes occurred around the focal area) in the period from June 14 to Sep. 30 from the JMA unified catalog. Number of P -wave arrival time and S -wave arrival time are 562857 and 452030, respectively. In addition, differential times obtained with a cross-spectral analysis were used. We estimate the differential time from cross spectrum, which is calculated for the vertical component of motion in the 1.28 s interval including the initial P -wave or S -wave motions in a frequency range of 3–12 Hz. A total of 303839 P -wave and 26340 S -wave differential times obtained within 5 km of the hypocenter with coherence of 0.95 or higher were used. Total travel time residual is from 0.14 s to 0.06 s. Figure 3 shows the checkerboard resolu-

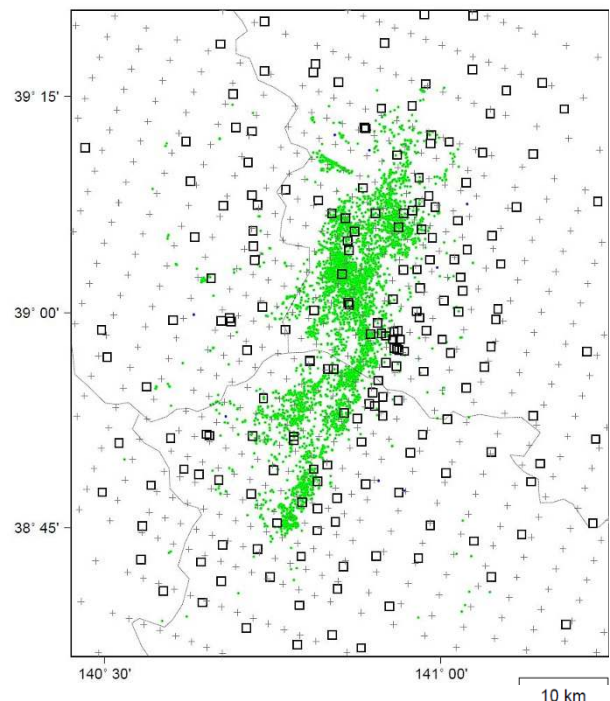


Fig. 2. Data set in this study. Open squares, small crosses, and green dots denote the stations, grids, and epicenters of aftershocks, respectively. We set the grids at depths of 0, 1, 3, 6, 9, 12, 15, 18, 24, 36, 48, 60 km.

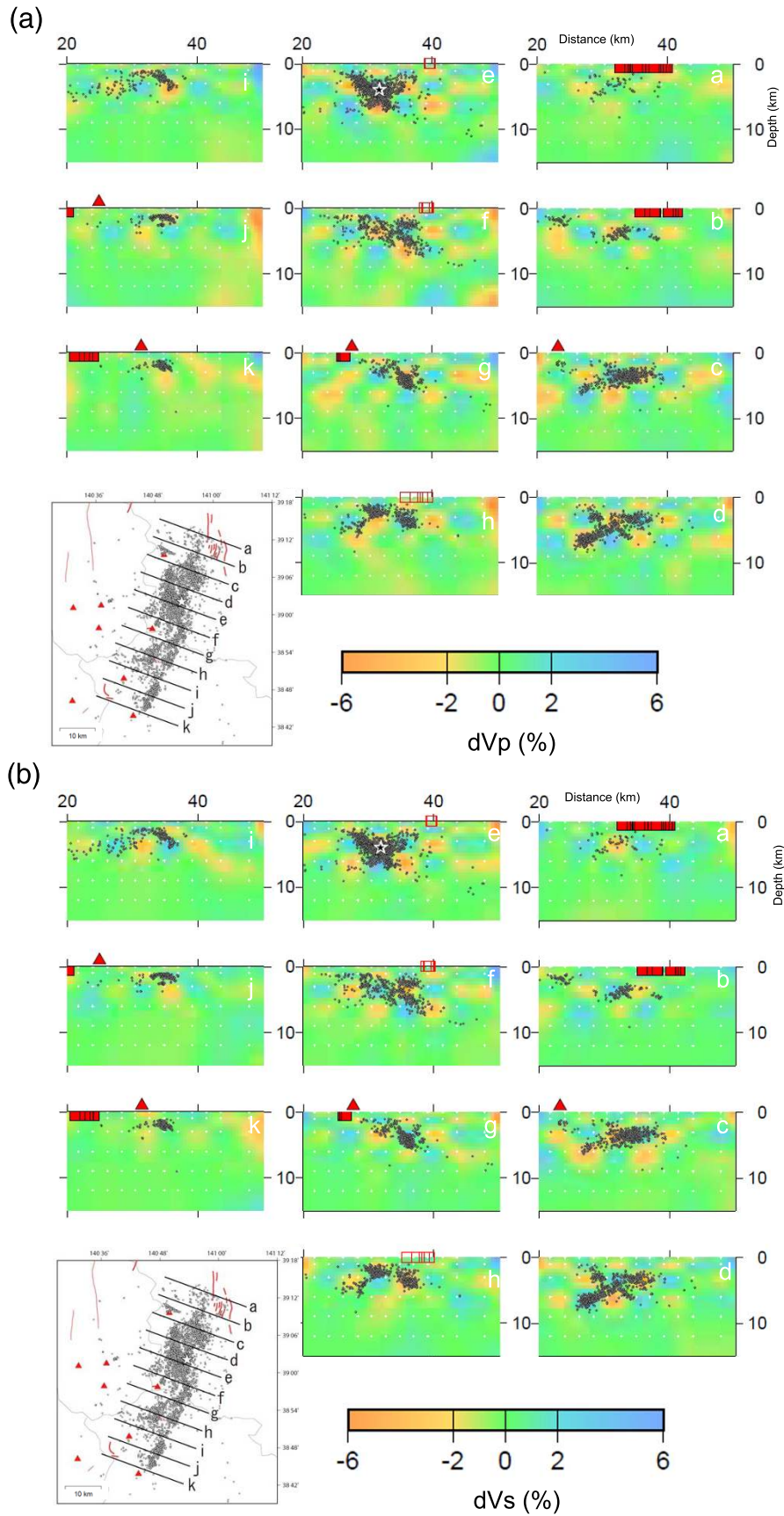


Fig. 3. Result of the checkerboard resolution test for (a) dV_p (perturbation in the P wave velocity) and (b) dV_s (perturbation in the S wave velocity)). Eleven across fault cross sections are shown. Locations of cross sections are shown in the insert map with the label of a to k. Red solid and open squares denote the location of the active fault and the surface deformation, respectively. Triangles denote volcanoes. Star denotes the mainshock hypocenter. White cross denote the grid used in the tomography.

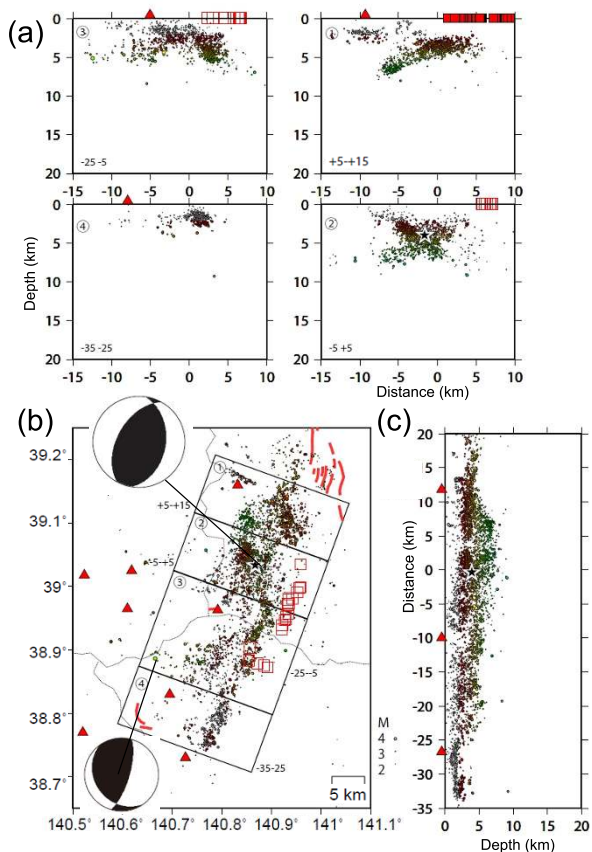


Fig. 4. Aftershocks, foreshocks and mainshock distribution. Small circles, black stars and white star denotes aftershocks, foreshocks and mainshock, respectively. Color of small circle means the depth of hypocenter. Triangles denote volcanoes. Open red squares denote the locations of the surface deformations. (a) The across fault cross section. Solid red squares denote the surface of the active faults. (b) Epicenter distribution. Bold lines denote the surface traces of the active faults. Large squares denote the locations of vertical cross sections in (a). Moment tensor solutions by F-net, NIED for the main shock and the largest aftershock are also shown. (c) The along-fault (NNE-SSW) cross section.

tion test in the second step. The amplitude of the velocity perturbation is ± 5 percents, and the size of the pattern is 2 grids in horizontal and 1 grid in vertical. We can see that the resolution become better and is estimated to be about 6 km in horizontal and 3 km in vertical in upper crust where the aftershocks are distributed both for P -wave and S -wave in this case.

3. Results

3.1 Distribution of hypocenters of mainshock, foreshocks and aftershocks using temporary observation data

The hypocenter distribution thus obtained is shown in Fig. 4. The aftershock region extends in the NNE-SSW direction for approximately 45 km along strike with a width of 15 km. The area in which the largest slip occurred during the mainshock (e.g. Ohta *et al.*, 2008), as will be discussed in more detail later, extends for 15–20 km SSW from the hypocenter of the mainshock, at a shallow depth. The aftershocks occurred in an area that was significantly elongated in the N-S direction compared to the major slip area of the mainshock.

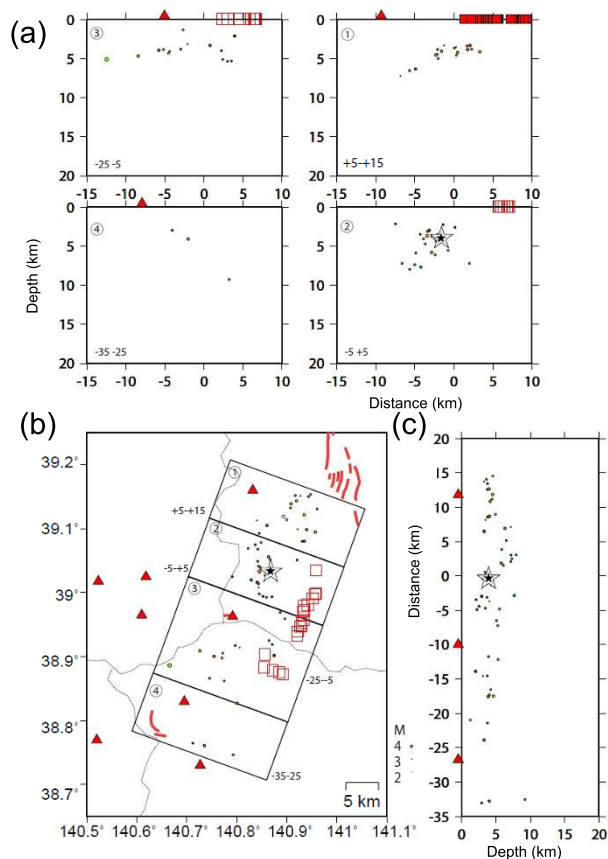


Fig. 5. Aftershocks for 1 hour, foreshocks and mainshock distribution. Details except moment tensor solutions are the same as Fig. 4.

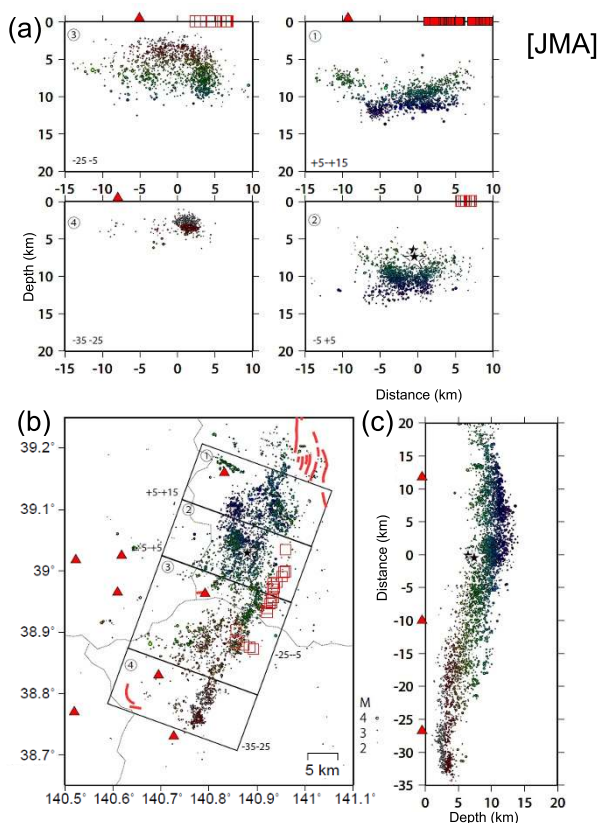


Fig. 6. Aftershocks, foreshocks and mainshock distribution from the JMA unified catalog. Details except moment tensor solutions are the same as Fig. 4.

In the vicinity of the mainshock (Fig. 4(a) 2), the distribution of aftershocks forms a plane that dips to the west at approximately 40° , similar to the angle of the fault plane of the neighboring earthquakes, the 2003 North Miyagi Earthquake (M 6.4) (Okada *et al.*, 2003; Umino *et al.*, 2003) and 1962 North Miyagi Earthquake (M 6.2) (Hasegawa *et al.*, 2005). This westward dipping aftershock alignment is thought to be along the major fault plane of the mainshock, as suggested by the GPS observation (cf. Ohta *et al.*, 2008). Note that “eastward” dipping aftershock alignment can be seen in the vicinity of the main shock (Fig. 4(a) 2).

The aftershock distribution is very complex but in the early stage it is relatively simple. In Fig. 5, we show aftershocks only for one hour just after the mainshock. Near the mainshock, the westward dipping aftershock alignment seems to be dominated in the earlier stage. This westward dipping alignment is a dip angle of 45 degrees. This angle is consistent with the westward dipping fault plane of the focal mechanism.

On June 14, immediately prior to the 2008 earthquake, an M 0.6 foreshock occurred at 8:01 and an M 1.6 foreshock occurred at 8:11 (see Fig. 4). Both are very close to the mainshock.

Ground deformation would be caused by this earthquake has been confirmed (e.g. Toda *et al.*, 2008), and location of the deformation belt is closely located with the Mochikorobashi-Hosokura Tectonic Zone (MHTZ). The shallow extension of the aftershock distribution is in approximate agreement with the position of ground deformation (Fig. 4). In the north of the source region, the shallower extension of the aftershock distribution meets roughly near the surface trace of the Kitakami Lowland fault (cf. Sato *et al.*, 2008).

We can see spatial variation of lower limit of aftershock distribution along the focal area shown in Fig. 4(c). In the central part of the aftershock region, in the vicinity of the mainshock, the lower limit of aftershocks is relatively deep (~ 10 km), while that the northernmost and southernmost parts tends to be shallower (< 5 km) (Figs. 4(b) and (c)). The spatial distribution of the lower limit of aftershocks is expected from the microearthquakes prior to the 2008 earthquake, and represents the regional variation in the seismogenic layer in this region (Hasegawa *et al.*, 2000). The lower limit of the seismogenic layer corresponds to the boundary between brittle and ductile deformation, and is determined by temperature. The northern edge (Mt. Yakeishi-dake) and southern edge (the Onikobe and Naruko volcanoes) of this region would be at higher temperature than the central part, resulting in shallower lower limit of seismicity in these regions.

Figure 6 shows the mainshock and aftershock distribution from the JMA Unified catalog (Japan Meteorological Agency, 2008). No clear aftershock alignment can be seen and the focal depths of the aftershocks in central and northern parts of the aftershock area are determined to be at larger depth, comparing with the aftershock distribution obtained in this study. This is due to the JMA catalog does not use the dense aftershock observation data and does not take the three dimensional seismic velocity structure into account.

4. Preceding Seismic Activity

It has also been confirmed that preceding seismic activity occurred in the vicinity of the mainshock of the 2008 earthquake (see Fig. 7), including an M 4.5 earthquake on April 19, 1999, and an M 4.9 earthquake on February 11, 2000. We relocated these earthquakes and their aftershock by the same procedure. Aftershock alignments of these two earthquakes follow on a shallow extension of the westward dipping plane of aftershocks following the 2008 Iwate-Miyagi Earthquake. It is therefore inferred that these preceding events occurred on the same fault plane as the 2008 earthquake. The aftershock and source regions of the 1999 and 2000 earthquakes are within the aftershock region of the 2008 earthquake, although the aftershock activity related to the 2008 event was relatively weak in the aftershock areas of the 1999 and 2000. Such preceding earthquake activity near the mainshock hypocenter has been reported for the 2000 Western Tottori earthquake (M 7.3) (Shibutani *et al.*, 2002). This suggests that slip occurred during the 1999 and 2000 earthquakes on the same fault plane of the 2008 latest earthquake, resulting in a release of strain and causing the relatively low aftershock activity following the 2008 earthquake.

4.1 Comparison of the aftershock distribution with the seismic velocity structure

Figure 8 shows the close up image near the fault for P -wave velocity (V_p) distribution. Near the mainshock hypocenter (cross section e), lower seismic velocity hanging wall for the westward dipping aftershock alignment can be imaged and the westward dipping aftershock alignment seem to be almost parallel to the iso-velocity contour of P wave velocity (V_p).

This observations means that the fault plane of the present earthquake is possibly correspond to the velocity changing zone and hanging wall has lower velocity than the footwall. This is the same as the previous compressional earthquakes as the 2003 northern Miyagi earthquake and others recently occurred in NE Japan (e.g. Okada *et al.*, 2005, 2007a).

We can also see the eastward-dipping aftershock alignment. Crustal deformation detected by InSAR suggests the possible eastward-dipping fault plane which seem to almost correspond to this eastward-dipping aftershock alignment (e.g. Takada *et al.*, 2009). The hanging wall for these eastward-dipping alignments do not have a lower seismic velocity than the footwall (Figs. 8(g), (h) and (i)). This is the same as for the conjugate M 6 aftershock of the 2004 Mid Niigata (Chuetsu) earthquake (e.g. Okada *et al.*, 2005). This might suggest eastward-dipping alignment may mean relatively newly developed fault or the fault which is less developed in Miocene in comparison with the major westward-dipping fault plane.

Note that the some part of low-velocity body in the upper crust has low V_p/V_s (S -wave velocity; V_s) (Fig. 9). Matsubara *et al.* (2004) found a seismic low-velocity body with low V_p/V_s in the upper crust beneath the northern part of the Kitakami Lowland fault. Okada *et al.* (2007a) also found a seismic low-velocity body with low V_p/V_s around the fault in the upper crust of the 2003 northern Miyagi earthquake. The low velocities with low V_p/V_s can be in-

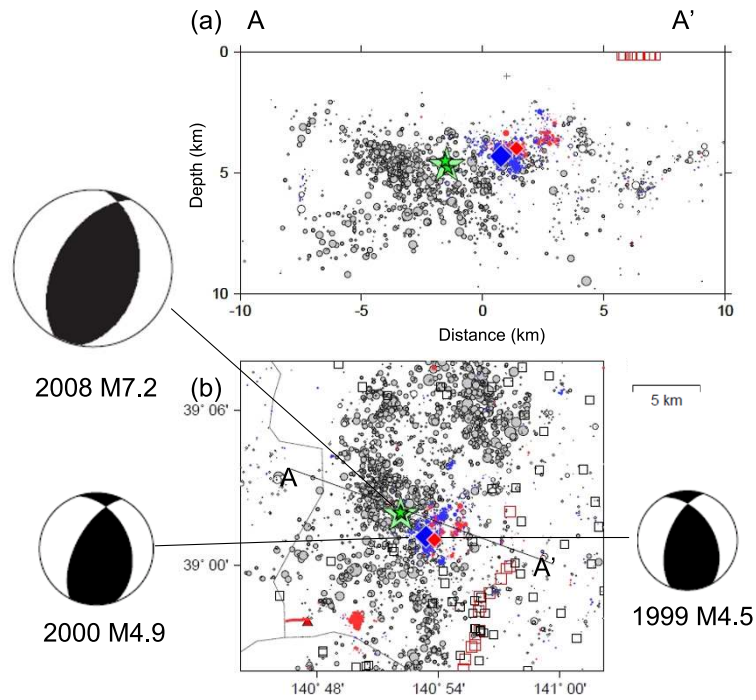


Fig. 7. Hypocenter distribution of the 2000 M 4.9 and 1999 M 4.3 earthquakes. The events in 2000 and 1999 are shown in blue and red, respectively. Mainshocks are shown by diamonds. The aftershocks, foreshocks and mainshock in 2008 are shown in gray circles, green small stars and green large star, respectively. Open red squares denote the locations of the surface deformations. (a) The across-fault cross section in a width of 5 km. (b) Epicenter map. Location of the cross section is shown by line. Focal mechanisms (NIED moment tensor solutions) of the 2000 M 4.9, 1999 M 4.3 and 2008 M 7.2 earthquakes are also shown. Black open squares denote the stations.

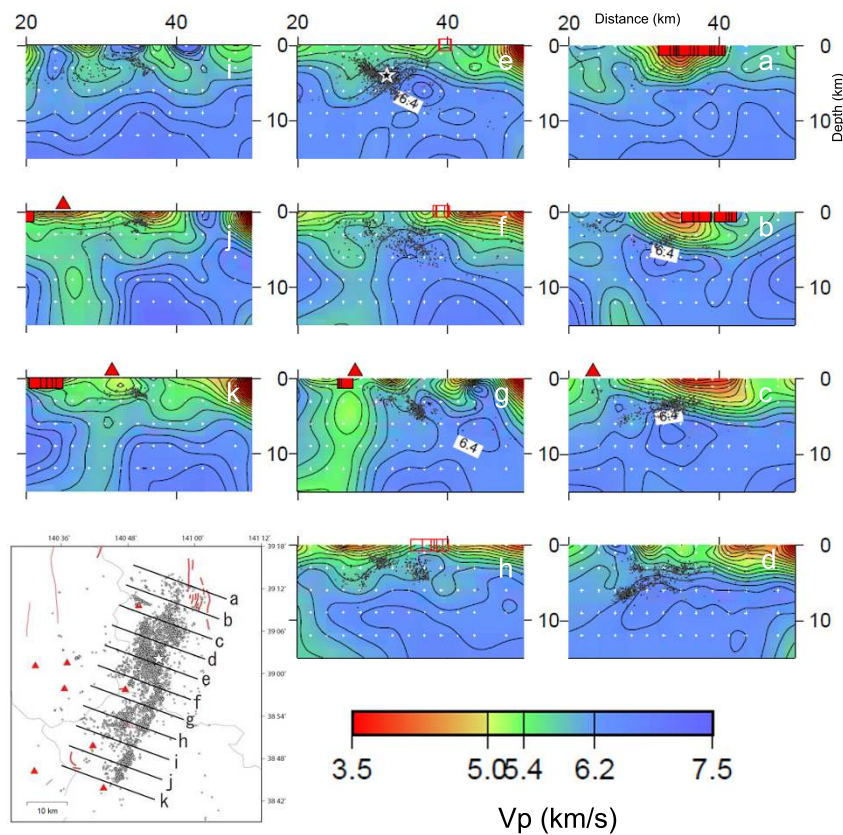


Fig. 8. V_p distribution. Eleven across fault vertical cross sections are shown. Locations of cross sections are shown in the insert map with the label of a to k. Red solid and open squares denote the location of the active fault and the surface deformation, respectively. Triangles denote volcanoes. Contour interval is 0.2 km/s. White cross denote the grid used in the tomography.

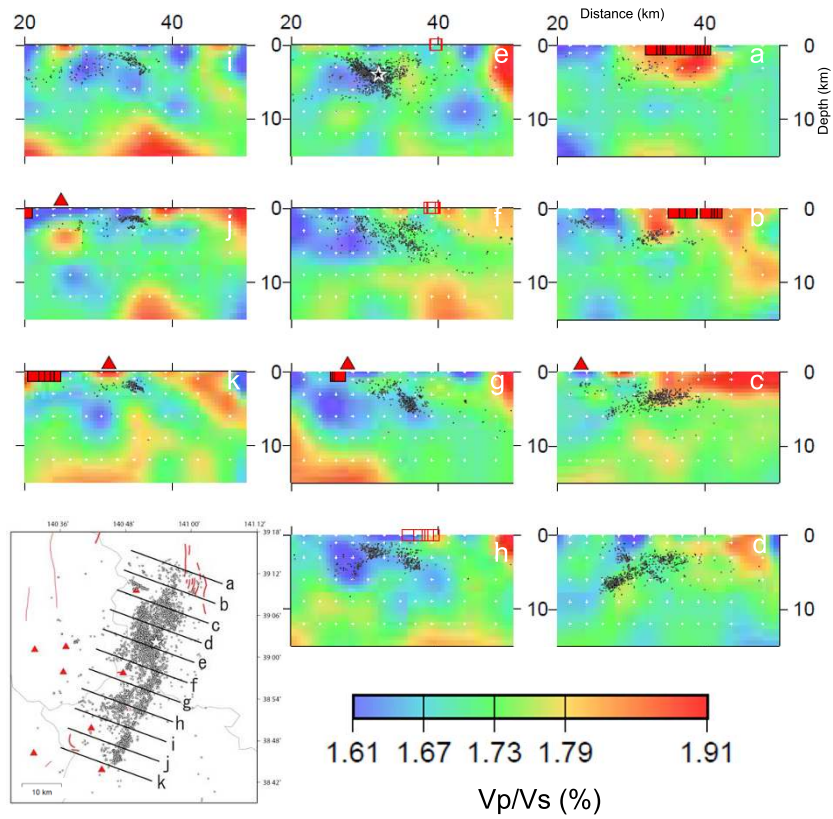


Fig. 9. V_p/V_s distribution. Eleven across fault cross vertical sections are shown. Locations of cross sections are shown in the insert map with the label of a to k. Red solid and open squares denote the location of the active fault and the surface deformation, respectively. Triangles denote volcanoes. White cross denote the grid used in the tomography.

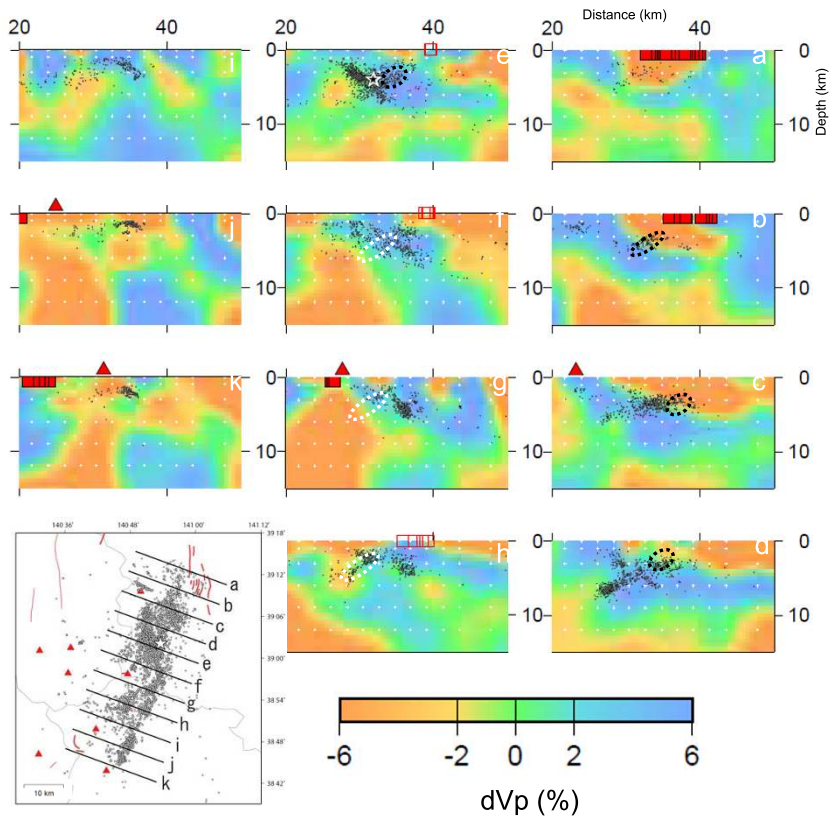


Fig. 10. V_p perturbation distribution. Eleven across fault vertical cross sections are shown. Locations of cross sections are shown in the insert map with the label of a to k. Red solid and open squares denote the location of the active fault and the surface deformation, respectively. Triangles denote volcanoes. Circles by broken lines (in f, g, and h) show the high velocity areas along the fault plane where the large coseismic slip occurred (cf. Ohta *et al.*, 2008). White cross denote the grid used in the tomography. Circles by black broken lines (in b, c, d and e) show the areas along the fault plane where the large postseismic slip occurred (cf. Iinuma *et al.*, 2008).

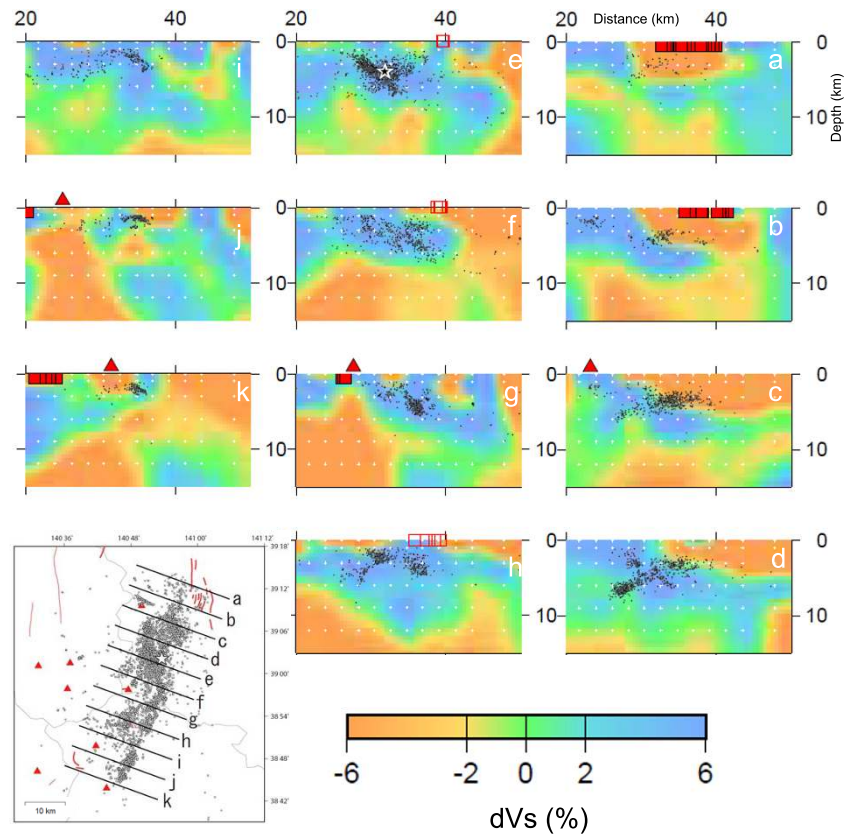


Fig. 11. V_s perturbation distribution. Eleven across fault vertical cross sections are shown. Locations of cross sections are shown in the insert map with the label of a to k. Red solid and open squares denote the location of the active fault and the surface deformation, respectively. Triangles denote volcanoes. White cross denote the grid used in the tomography.

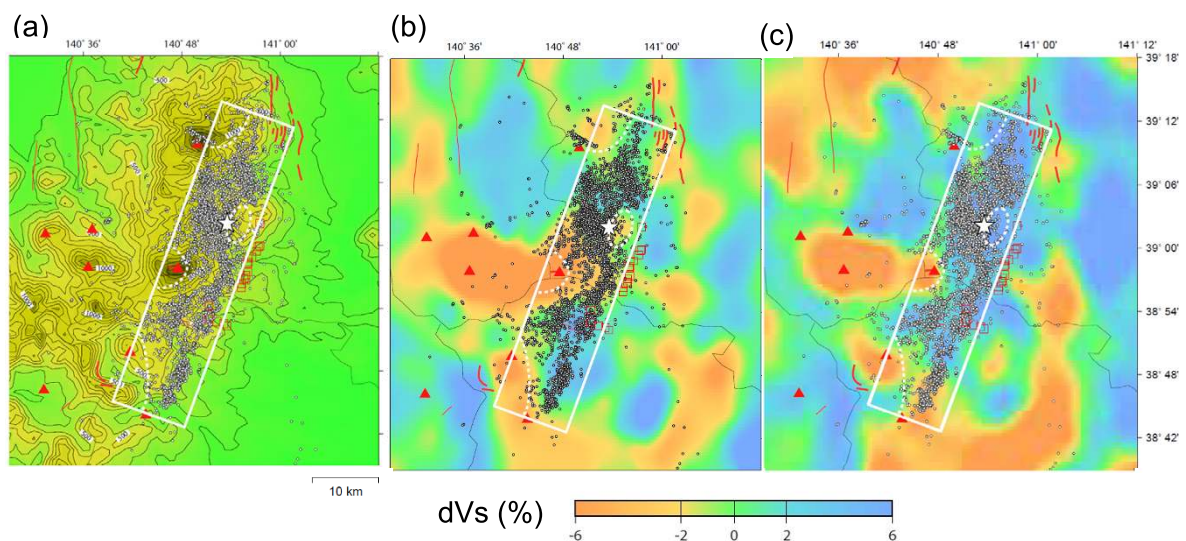


Fig. 12. (a) Topographic map with aftershocks. White rectangular denote the spatial extent of the aftershock area, and the areas with less aftershock are shown by broken lines. (b) V_s perturbation at a depth of 9 km and (c) 6 km.

terpreted as the existence of high-aspect ratio pore with free aqueous fluids (Takei, 2002).

5. Discussion

5.1 Comparison with fault model and coseismic slip

As discussed above, we relocated hypocenters of the foreshocks, main shock and aftershocks of the 2008 earth-

quake. The source fault model and slip distribution for this earthquake is estimated by seismic waveforms and geodetic data (e.g. Asano and Iwata, 2008; Ohta *et al.*, 2008). For example, GPS data indicate that the fault plane is westward dipping and the length of the major slip region is approximately 30 km (Ohta *et al.*, 2008). According to the detailed slip distribution on the fault plane, the major slip area was

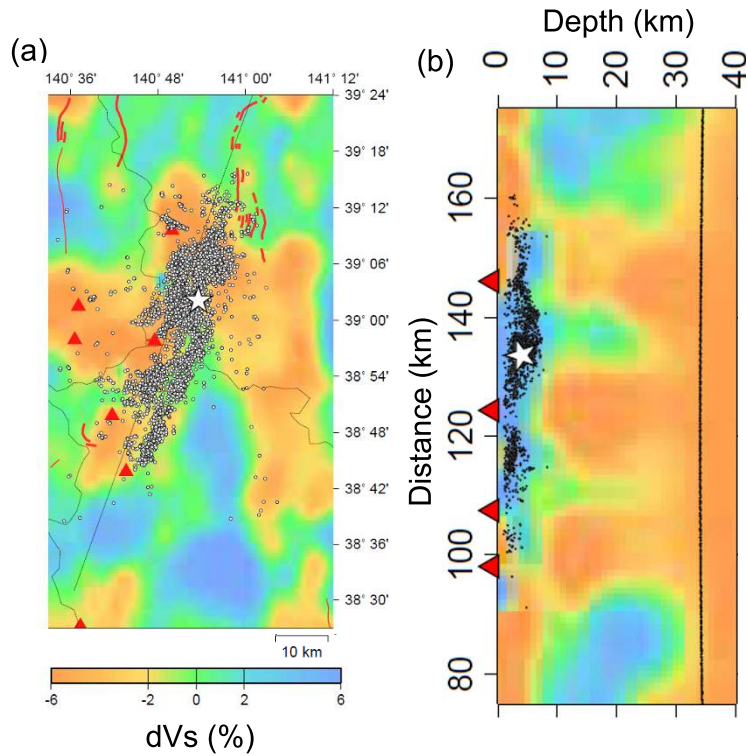


Fig. 13. (a) V_s perturbation at a depth of 24 km. Small circles and star denote the aftershocks and mainshock, respectively. Black line denotes the location of cross section. Triangles denote volcanoes. (b) The along-fault vertical cross section. Bold line denotes the location of the Moho discontinuity (Zhao *et al.*, 1990).

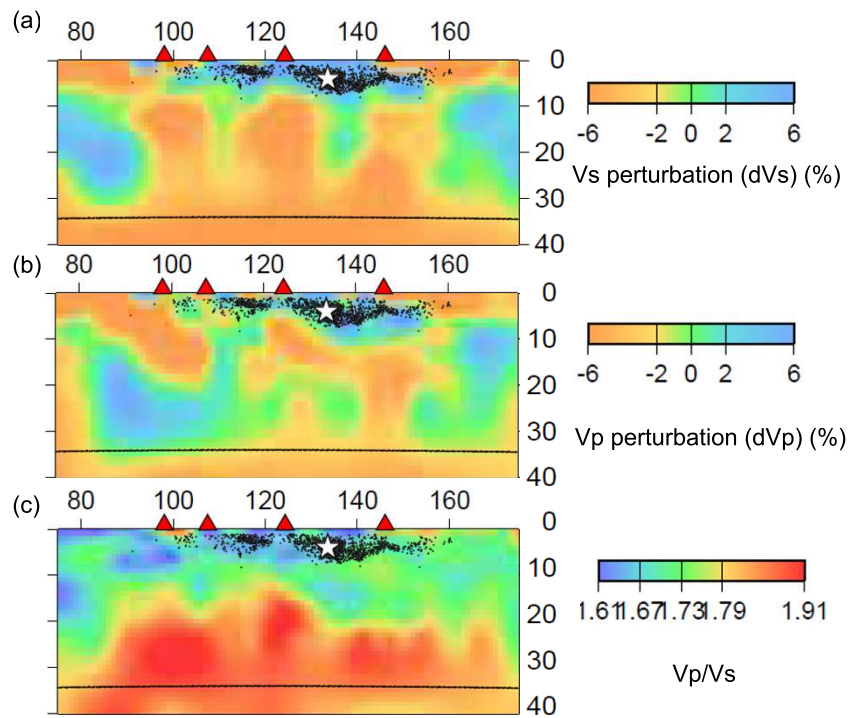


Fig. 14. The along-fault vertical cross section. Bold line denotes the location of the Moho discontinuity. Triangles denote volcanoes. (a) dV_s , (b) dV_p and (c) V_p/V_s .

south of the main shock in a shallow area and the estimated maximum slip is as large as 5 m.

Figure 10 shows the comparison of V_p perturbation distribution and location of large coseismic slip. In the central to the southern part (f–h), the higher velocity region

($\delta V_p/V_p > \sim 0$) extends to the shallower part or the hanging wall side, and the aftershock distribution, the seismic velocity structure, and the relation between them are complex. Large coseismic slip area (shown by circle) has been estimated (Ohta *et al.*, 2008) in this part, and it seems to be

in the complex and relatively high velocity area. This correspondence between high-velocity body and asperity has observed also in the 2003 northern Miyagi earthquake (M 6.4) in NE Japan (Okada *et al.*, 2007a), the 2004 Mid Niigata earthquake in central Japan (Okada *et al.*, 2005, 2006), the 1995 southern Hyogo (Kobe) earthquake (M 7.2) (Okada *et al.*, 2007b), the 2005 West off Fukuoka Prefecture earthquake (M 7.3) (Hori *et al.*, 2006) and Park eld, California (Michael and Eberhart-Phillips, 1991; Eberhart-Phillips and Michael, 1993). Such high-velocity area might act as “asperity” which can store large strain and occur large slip (e.g. Hasegawa *et al.*, 2007). In contrast, post-seismic slip areas (Iinuma *et al.*, 2008) are distributed in the shallow low-velocity zone in the northeastern part of the focal area (cross sections a–d). These low velocity area would correspond to the non-asperity areas of a-seismic deformation surrounding the asperity.

5.2 Relation with volcanoes and deep crustal fluid

A series of vertical cross-section of the distribution of S -wave velocity perturbation in the WNW-ESE direction (across the fault) is shown in Fig. 11. The aftershocks tend to be distributed in the high-velocity region, and the low-velocity region is distributed just below the hypocenter of the main shock (cross-section e). High electronic conductive region can be detected in this low-velocity region (e.g. Mishina, 2009; Sanakana *et al.*, 2009). This low-velocity region (with moderate to relatively high V_p/V_s , Fig. 11) could be interpreted as the region with high amount of fluid (Takei, 2002) and corresponds to crustal fluid upwelling.

Note that we can see with the shallow low-velocity and high- V_p/V_s regions at and around the surface trace of faults. This region can be interpreted as the highly-fractured region includes high amount of fluid, which would be originated from deeper part.

Such low-velocity regions beneath the focal area of inland earthquakes in Japan can be commonly seen and interpreted as the region with overpressurized fluid, which promote the occurrence of inland earthquake; for example, the 1995 southern Hyogo (M 7.2) (Zhao *et al.*, 1996; Zhao and Negishi, 1998), the 2000 western Tottori (M 7.3) (Zhao *et al.*, 2004), the 1962 northern Miyagi (M 6.2) (Nakajima and Hasegawa, 2003), the 2004 Niigata-Chuetsu (M 6.8) (Okada *et al.*, 2006; Wang and Zhao, 2006) and the 2007 Noto-Hanto (M 7.3) and Niigata-Chuetsu-Oki (M 6.8) (Nakajima and Hasegawa, 2008). This suggests that crustal fluid was involved also in the occurrence of the 2008 earthquake. As shown before, the seismic velocity structure also suggests the present earthquake would be a compressional inversion earthquake. The over-pressurized fluid imaged as low-velocity zone is the plausible cause of the reactivation of such a compressional inversion fault (Sibson, 1990).

A comparison of the aftershock distribution with the distribution of S -wave velocity perturbation at a depth of 6 km and 9 km and topographical map is shown in Fig. 12. Low-velocity regions, which might correspond to magma upwelling, are distributed in the vicinity of Mts. Yakeishidake and Kurikoma, and the Onikobe and Narugo volcanoes, all of which are active volcanoes. These results show the low aftershock activity in these regions. This means

the low-velocity regions beneath the volcanoes have higher temperature, which make the crustal rocks aseismic.

In this study, we obtained the seismic velocity structure in the whole crust by using the result in the previous study (Okada *et al.*, 2010), in which we have obtained the seismic velocity beneath the focal area of the present earthquake, as an initial velocity model. We compare the seismic velocity structure in the whole crust and the precise aftershock distribution obtained in this study. A vertical cross-section of the distribution of S -wave velocity perturbation in the NNE-SSW direction (along the fault) is shown in Fig. 13. In the lower crust, distinct low-velocity zone exists just beneath the aftershock focal area as shown in the previous study (Okada *et al.*, 2010). The spatial extent of this low velocity zone seems to be almost same as the aftershock focal area. This low velocity zone becomes to be divided in three parts just beneath the volcanoes. The mainshock hypocenter is located just above one of the low-velocity zones. Deep limit of aftershock tend to be shallower where the low-velocity zone exist shallower beneath volcanoes. The aftershocks are distributed within high-velocity areas in the upper crust.

Figure 14 shows the along-fault vertical cross section for V_s perturbation (dV_s) (same as Fig. 12(b)), V_p perturbation (dV_p) and V_p/V_s . We can see that the low-velocity zone has high V_p/V_s value in the lower crust, and moderate to low V_p/V_s value in the upper crust (see also Fig. 11). The high V_p/V_s value in the lower crust can be interpreted as the area with high amount of melt and the moderate to low V_p/V_s value in the upper crust can be interpreted as the area of relatively high aspect ratio pore including water (Takei, 2002).

This low-velocity zone in the lower crust would correspond to region of partial melting. High temperature partial melting zone and fluid released from it would promote the local crustal deformation and causes stress concentration in the surrounding area to occur the present earthquake.

6. Conclusions

Dip of the westward dipping fault plane is estimated to be about 40–50 degrees from aftershock alignment near the mainshock hypocenter. “Eastward dipping” aftershock alignment can be seen in the central part. Low seismic velocity hanging wall for the westward dipping aftershock alignment can be imaged near the mainshock hypocenter. Low velocity zone is imaged beneath the focal area (the hypocenter of mainshock, in particular). Lower limit of aftershock varies spatially and becomes shallower near the volcanoes, where distinct low-velocity areas are distributed in the shallower part. The aftershocks tend not to occur in low-velocity regions, where the temperature would be relatively high. Large coseismic slip areas are also not distributed in low-velocity regions but can be seen in the high velocity areas. The present earthquake is possibly a fluid-driven compressional inversion earthquake but strongly influenced by the recent volcanic activity, thermal structure and complex fault system.

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