Hypocenter distribution of the main- and aftershocks of the 2005 Off Miyagi Prefecture Earthquake located by ocean bottom seismographic data

Ryota Hino[1], Yojiro Yamamoto[1], Asako Kuwano[1], Minoru Nishino[1], Toshihiko Kanazawa[2], Tomoaki Yamada[2], Kazuo Nakahigashi[2], Kimihiro Mochizuki[2], Masanao Shinohara[2], Kouetsu Minato[3], Gen Aoki[3], Nariaki Okawara[4], Masayuki Tanaka[4], Masao Abe[4], Eiichiro Araki[5], Shuichi Kodaira[5], Gou Fujie[5] and Yoshiyuki Kaneda[5]

[1] Graduate School of Science, Tohoku University, Sedai 980-8578, Japan.

[2] Earthquake Research Institute, The University of Tokyo, Tokyo, 113-0032, Japan.

[3] Sendai District Meteorological Observatory, Japan Meteorological Agency, Sendai, 983-0842, Japan.

[4] Seismological and Volcanological Department, Japan Meteorological Agency, Tokyo, 100-8122, Japan

[5] Japan Agency for Marine-Earth Science and Technology, Yokosuka, 237-0061, Japan.

Abstract

The hypocenter distribution of the 2005 Off Miyagi Prefecture Earthquake and its aftershocks is estimated by using five ocean bottom and six onshore seismic stations data around the rupture area of the earthquake. The epicenter of the mainshock is relocated at (38.17°N, 142.18°E) and the focal depth is estimated to be 37.5 km. The aftershocks surrounding the mainshock hypocenter forming a several clusters concentrate along a distinct landward dipping plane corresponding to the plate boundary imaged by the previous seismic experiment. The strike and dip angles of the plane agree well to those of the focal mechanism solution of the mainshock. The size of the plane is about 20 x 25 km^2, in strike and dip directions, similar to that of the large coseismic slip area. The up dip end of the planar distribution of the aftershocks corresponds to the bending point of the subducting oceanic plate, suggesting that the geometry of the plate boundary affects the spatial extent of the asperity of the 2005 earthquake.

1. Introduction

The landward slope area of the Japan Trench subduction zone is characterized by active interplate seismicity and large earthquakes with magnitudes more than seven have occurred repeatedly. Yamanaka and Kikuchi (2004) have shown that these large interplate earthquakes are repeating ruptures of asperities, areas of large coseismic slip but locked during interseismic period along the surface of the subducting Pacific plate. In the middle part of the subduction zone, the M 7.5 class earthquakes off Miyagi prefecture are known to occur with a recurrence interval of about 40 years. The most recent event of this earthquake sequence occurred in 1978, 27 years ago from now, and the Japanese government announced that the probability of the occurrence of such a M 7.5 class earthquake within next ten years is about 50 % (HERP, 2003). On August 16 2005, an earthquake of M7.2 occurred off Miyagi prefecture. The focal mechanism solution of the earthquake was of a thrust fault type (e.g. F-Net, NIED, 2005) indicating that this event was an interplate earthquake, but its seismic moment was 5.4 x 10^{19} Nm (e.g. F-Net, NIED, 2005), significantly smaller than that of the earthquake forecasted to occur. Okada et al. (2005) proposed that the 2005 earthquake was a re-rupturing of the one of the asperities of the preceding 1978 earthquake. If this is the case, the rupture area of the 2005 is an asperity that ruptures repeatedly in the consecutive earthquakes and it is very important to reveal its exact location to understand the natures of asperities.In order to clarify the spatial and temporal distribution of the seismicity around off Miyagi prefecture area, we have made a series of ocean bottom seismographic observations since 2002 by repeating deployment and retrieval of pop-up type ocean bottom seismographs (OBSs). At the occurrence of this earthquake, 15 OBSs were in operation. After the occurrence of the M 7.2 earthquake, we decided to retrieve five OBSs deployed around the epicenter to know the precise hypocenter locations of the mainshock and subsequent aftershocks as soon as possible. This paper describes preliminary results of the hypocenter determination usingthe five OBSs data, which were retrieved 12 days after the mainshock occurrence, to show the location and geometry of the fault ruptured by the 2005 earthquake. Since some of the OBSs observing the 2005 earthquake are in operation until May 2006, we will present final results using all the OBS data after that.

2. Data and Analyses

The OBSs used in this study are of a free-fall/pop-up type developed by Kanazawa and Shiobara (1994), equipped with a three component geophone. The seismic waveform data are continuously recorded onto hard disk drives after A/D conversion (20bit/128Hz) The timing accuracy is kept within 0.05 sec by using a high precision quartz oscillator calibrated to a GPS clock before and after the observation. The OBSs were deployed in July 2005 by R/V Kofu-maru and were retrieved by R/V Yokosuka in end of August, 12 days after the occurrence of the 2005 Off Miyagi Prefecture Earthquake, providing continuous waveform records from July 13 to August 28. The locations of the OBS stations are shown in Fig. 1 and Table. 1, and they were obtained by acoustic triangulation measurements.

In this study, we relocate the hypocenters of the mainshock occurred at 11:46 on Aug. 16 and of aftershocks taking places until August 24, the occurrence of another large (M 6.3) earthquake near the Japan Trench. Since the epicenter of this earthquake is too far (38.44°N, 143.09°E, according to the Japan Meteorological Agency catalogue) from the OBS network to locate precisely even using our OBS data, we did not relocate hypocenters of this M 6.3 earthquake and its aftershocks in this study. We picked the P and S waves arrival times of the target events from the OBS records and also from records of six onshore stations (Fig. 1 and Table. 1) nearby the aftershock region, operated by Tohoku University and JMA.

Using the picked arrival time data, hypocenters were calculated assuming 1-D seismic velocity structure models shown in Fig. 2. Firstly, absolute arrival time data were inverted for hypocenter locations, and then we applied the double-difference (DD) method (Waldhouser and Ellsworth, 2000) to the caclulated hypocenters for obtaining the final hypocenter distribution. We referred to the Vp structure model estimated by the marine seismic exploration conducted in this area (Ito et al., 2005) and a Vp/Vs ratio of 1.73 is assumed.

For the arrival time data at the OBS stations, we applied corrections to account for the travel time delays due to the sedimentary layer with very low Vp and Vs covering the ocean floor. The delay times for P and S waves can be estimated from the Vp, Vs and the thickness of the layer. The Vp and Vs are assumed to be constant and 2.0 and 0.57 km/s, respectively, and variation of the sediment thickness is estimated from the arrival time difference between the P wave and the S waves converted from the P wave at the basement of the sedimentary layer (e.g., Hino et al., 2000), for each of the OBS stations. Observed PS-P times for five OBS stations are tabulated in Table. 1.

The hypocenter coordinates calculated from the arrival time data thus corrected assuming the 1-D velocity structure were used as the initial locations of the hypocenters in the DD location analysis. Double differences of the travel times are measured for the event pairs with separations of less than 15 km. We did not apply any cross correlating measurements to get the travel time differences. They were obtained from the arrival time data picked by operators. Both P and S waves data were used in the DD hypocenter relocation.

3. Results

In Fig. 1, the epicenters determined by the ordinary hypocenter locations using absolute travel times are shown. Hypocenters with rms travel time residuals of less than 0.3 s are plotted. The relocated epicenters show more compact distribution than those from the JMA catalogue. Although no systematic differences are recognized between the relocated and the catalogued aftershock distribution, the epicenter of the mainshock is relocated at (38.17°N, 142.18°E), about 8 km west of the epicenter reported by JMA. Although the catalogued mainshock epicenter is located at the eastern edge of the aftershock distribution, the relocated one is in the middle of one of the aftershock clusters.

The focal depth distributions according to the JMA catalogue and relocated by using the OBS data are shown in Figs. 3a and 3b, respectively. It is evident that the resolution of focal depths is considerably improved by using the OBS data. Most of the relocated hypocenters are concentrated along a landward dipping plane corresponding to the fault plane of the mainshock, the plate boundary. The hypocenter of the mainshock by JMA is determined below the landward dipping aftershock plane (Fig. 3a) and remains below the aftershock distribution even the OBS data are included (Fig. 3b). But the focal depth of the mainshock is determined almost the same as the surrounding aftershocks when we use only P wave arrival time data (Fig. 3c), indicating that the S arrival time data account for the deeper hypocenter of the mainshock.

Fig. 3d show travel time residuals of P and S waves for the mainshock and the aftershocks whose locations are within 2 km distance from the mainshock. The residuals are calculated using the hypocenter locations determined by the P wave arrival time data only. The S residuals are less than 0.5 s for most of the aftershocks even the hypocenters are determined without S wave data, indicating the Vp/Vs ratio assumed for our hypocenter determination is reasonable. Notwithstanding this, the residuals for the mainshock exceed 1 s at many seismic stations and amount to more than 2 s for several stations. For this reason, we excluded the S arrival times of the mainshock from our data set.

Figure 4 is the hypocenter distribution of the mainshock and aftershocks of the 2005 Off Miyagi Prefecture Earthquake. Gray dots are the results of the ordinary hypocenter determination. Using these hypocenters as the initial locations, we applied the DD location method to obtain black dots in the figure. The hypocenter location of the mainshock did not move substantially by the DD relocation analysis. The focal depth of the mainshock is estimated to be 37.5 km.

The epicenters of the mainshock and a number of the aftershocks form an 'L' letter shaped clusters (we call this "main cluster" hereafter). Two arms of the 'L' are orthogonal to each other and have almost the same length, about 15 km. The mainshock is included in the WNW-ESE trending arm. The hypocenters belonging to the main cluster and its surrounding area, with about 20 and 25 km spans in strike and dip direction, concentrate well to a landward dipping plane. The plane has a strike of 197° and a dip of 24°, and its depth ranges from 30 to 45 km. It is interesting that the directions of the two arms almost coincide with the strike and dip direction of the landward dipping plane.

The aftershocks activity outside the planar structure zone is quite sparse and few evident clusters can be seen and it is difficult to image the overall shape of the aftershock distribution due to the sparseness. The hypocenters in the western part seem to be along the extension of the plane of the main cluster aftershocks down to about 50 km depth although focal depth distribution is more diffused than in the main cluster. To the east of the main cluster, there are two active clusters. The hypocenters in these clusters are more scattered in focal depths and do not seem to form a plane structure.

4. Discussion

The L-shaped main cluster and its surrounding aftershocks show distinct planar structure and the dip and strike of this plane coincide well to the focal mechanism solutions. For example, the dip and strike of the F-net solution are 22° and 197°, respectively. In Fig. 4, the coseismic slip of the 2005 Off Miyagi Prefecture Earthquake determined by teleseismic waveform data (Yaginuma et al., 2005) and spatial extent of the rupture area is almost the same as the size of the plane shaped aftershock distribution. These correspondences suggest that the aftershock distribution obtained by this study reflects exact location of the asperity of the 2005 earthquake.

The planar structure of the aftershocks is terminated by the NNE-SSW trending arm of the L-shaped main cluster and the hypocenters east of the cluster show diffused focal depth distribution. This suggests that the NNE-SSW arm marks the up-dip limit of the rupture area of the mainshock and the aftershocks in the eastern part may occur off the plane of the mainshock rupture, possibly within the subducting oceanic crust. In Fig. 4, the rupture area estimated by the teleseismic data extends more to the east than the location of the NNE-SSW trending arm and this seems to contradict to our interpretation. However the coseismic slip distribution may be shifted eastward compared to our aftershock distribution because Yaginuma et al [2005] assumed that that the rupture was started at the hypocenter location by JMA, about 8 km east of the relocated hypocenter. If they took the relocated hypocenter as the point of the rupture initiation, the eastward limit of the coseismic rupture should be coincide with the location of the NNS-SSW lineation of the aftershocks It is often reported that the aftershock activity tends to be inactive in the asperity region, where the amount of coseismic slip is large (e.g. Scholz, 2002, Hino et al., 2000). In the 2005 earthquake case, the aftershocks around the mainshock epicenter concentrate into small clusters and several areas of low seismicity can be the locations of the asperities ruptured by the mainshock. For example, the northeast-southwest trending arm of the L-shaped aftershock distribution seems to split the asperity imaged by the teleseismic study (Yaginuma et al., 2005) into the northern and southern portions, each of which corresponds to the aseismic zone surrounded by the aftershock clusters.

Okada et al. (2005) reanalyzed land seismic network data to compare the aftershock distribution of the 2005 earthquake with that of the 1978 and also with the background seismicity pattern and pointed out that the positions of active seismicity show little temporal variations. This implies the seismic coupling is controlled by persistent nature, such as structural heterogeneities along or in the vicinity of the plate boundary. In other words, the aftershock distribution reflects the spatial variation of the interplate coupling.

The plane formed by the main cluster events almost coincides with the plate boundary determined by the seismic exploration. Although the aftershock plane is slightly deeper than that of the plate boundary imaged by the seismic reflection signals, the dip angle is in good agreement. The focal depths determined here are heavily dependent on the S-P times at the OBS stations. Average of the focal depths changes according with the Vp/Vs values used for the estimation of station corrections and the travel time calculations, almost keeping the shape of the hypocenter distribution. However, we have no reliable information relevant to the Vs of the crust and the sedimentary layer in the offshore region of the northeastern Japan, and it is difficult to discuss whether the depth difference between the aftershock plane and the plate boundary is substantial.

Ito et al. (2005) pointed out that there are two bending points where the dip angle of the plate boundary changes suddenly and that the eastern edges of the rupture areas of the 1978 and 1981 Off Miyagi Earthquakes correspond to these bending points. The eastern limit of the planar aftershock distribution, which we interpret as the eastern limit of the rupture area of the 2005 earthquake, corresponds to the location of the bending point of the plate boundary as that of the 1978 does. As reviewed by Scholtz (2002), irregularities of fault geometry, such as bends, will be impediments to rupture propagation. The rupture propagation of the 2005 earthquake may be terminated by the bending of the fault plane located about 10 km up-dip of the hypocenter. King and Navelek (1985) explain that the termination of the rupture propagation is caused by the reduction of the stress at the tip of a growing fault by the deformation spread over a broad zone around the bending point. It is interesting that the aftershock plane is a little thicker at the up-dip end (pointed by an arrow in Fig. 4b) than the deeper part. The intraplate seismicity can be activated along the northeast-southwest trending arm of the L-shaped cluster as the result of the rupture termination process.

5. Conclusions

We relocate the hypocenters of the mainshock and aftershocks of the Off Miyagi Prefecture Eathquake, M 7.2 occurred on August 16, 2005 by using the data obtained by five ocean bottom seismographs and six onshore seismic stations.

By using the OBSs data, spatial resolution of the hypocenter distribution was improved considerably. The hypocenter of the mainshock is relocated at (38.17°N, 142.18°E) and the focal depth is estimated to be 37.5 km, about 8 km landward and 5 km upward of the JMA published hypocenter. The results of a hypocenter determination using absolute arrival times of P and S waves assuming a 1-D seismic structure model show that the mainshock hypocenter seems to be mislocated if the S wave arrival time data are included in the inversion.

Using the hypocenters determined by the conventional calculation as initial locations, we employ the DD location method to obtain the aftershock distribution as detailed as possible. Most of the aftershocks concentrate around the mainshock hypocenter and form several cluster. The most active cluster contains the mainshock hypocenter and has an L letter shape. These aftershock clusters form a distinct landward dipping plane with 15 and 25 km spans in strike and dip directions, respectively. The strike and dip of the plane are 197° and 24°, almost the same as those of the focal mechanism solution of the mainshock. The spatial extent of the plane of concentrating aftershocks may indicate the location of the rupture area of the mainshock. The aftershocks on the periphery of the rupture area show more diffused distribution partly due to the off plane aftershock activity.

The location of the plane of aftershock distribution corresponds to the plate boundary imaged by the previous wide-angle seismic reflection experiment. The imaged plate boundary changes its dip at about 30km depth and the location of this change seems to agree to the eastward limit of the in-plane aftershock activity. This correlation suggests that the shape of the plate boundary controls the spatial extent of the asperity of the 2005 earthquake.

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Table 1. Locations of seismic stations PS-P times used for travel time delay due to the sedimentary layer.

station	latitude	longitude	altitude (m)	PS-P time (s)
S01	38° 20.853'	142° 06.941'	-519	1.4
S02	37° 58.967'	142° 05.045'	-537	1.9
S03	38° 10.952'	142° 18.950'	-971	2.5
S04	38° 29.276'	142° 29.969'	-1104	2.5
S05	37° 56.963'	142° 28.889'	-1068	1.9
KN5	38° 16.578'	141° 34.956"	-435	—
EN3	38° 23.874'	141° 35.856'	-265	—
TKY	38° 45.486'	141° 13.308'	26	—
KSN	38° 58.590'	141° 31.806'	280	—
SN3	39° 08.406'	141° 45.816'	105	—
OURI	38° 27.438'	141° 20.718'	40	—

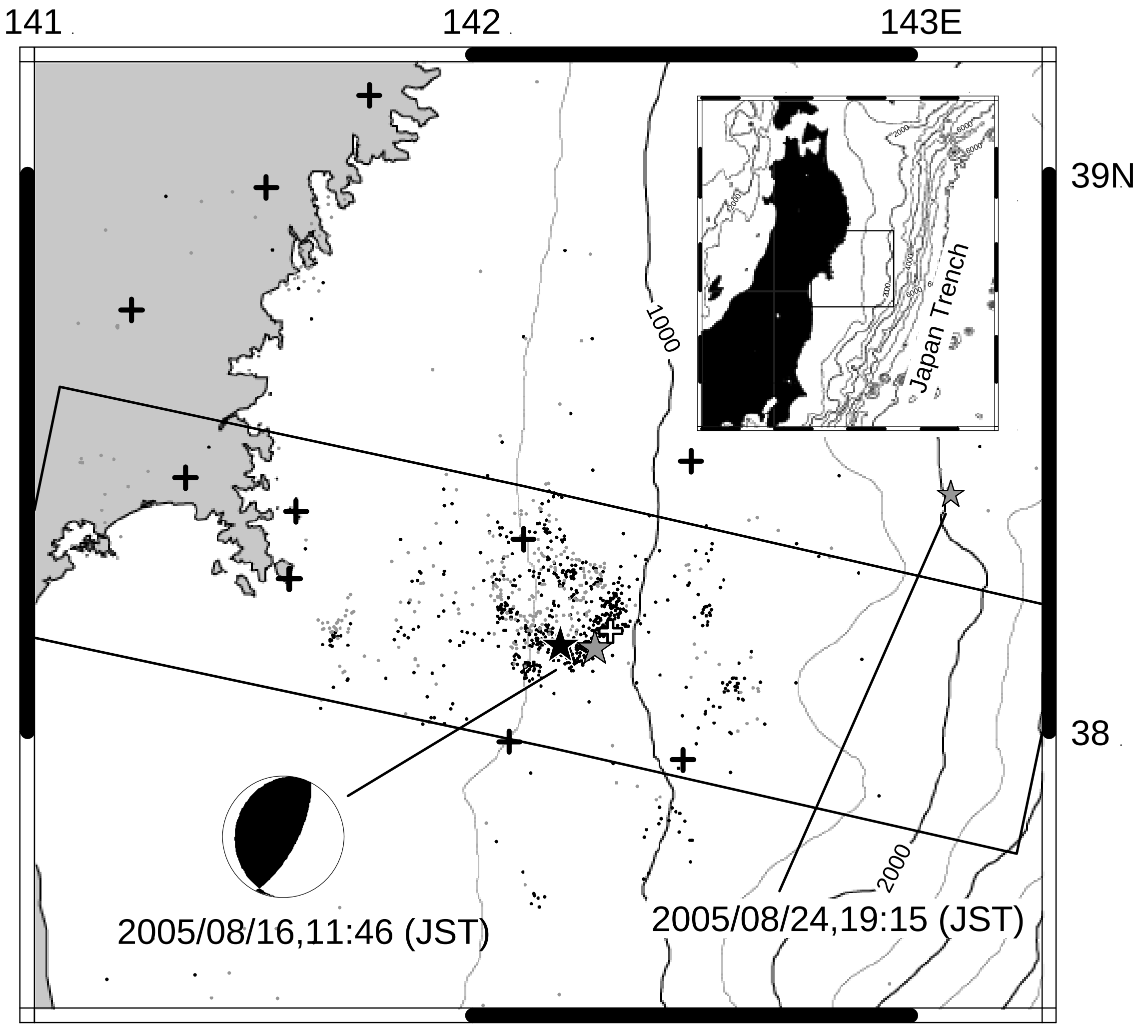

Fig. 1 Epicenter distribution of the mainshock and aftershocks of the 2005 Off Miyagi Prefecture Earthquake. Epicenters of the aftershocks occurred until August 24 are plotted. Gray stars are the epicenters of the mainshock and an M 6.3 earthquake occurred on Aug. 24 determined by Japan Meteorological Agency (JMA). Black star is the mainshock epicenter located by the conventional hypocenter determination of this study. Dots are aftershock epicenters (gray: JMA, black: this study). Crosses are the locations of the seismic stations, five offshore and six onshore. Focal mechanism solution by F-net NIED (2005) is also shown. Focal depth distribution of the hypocenters in the rectangle is shown in Fig. 3. Contours are isobaths in meter.

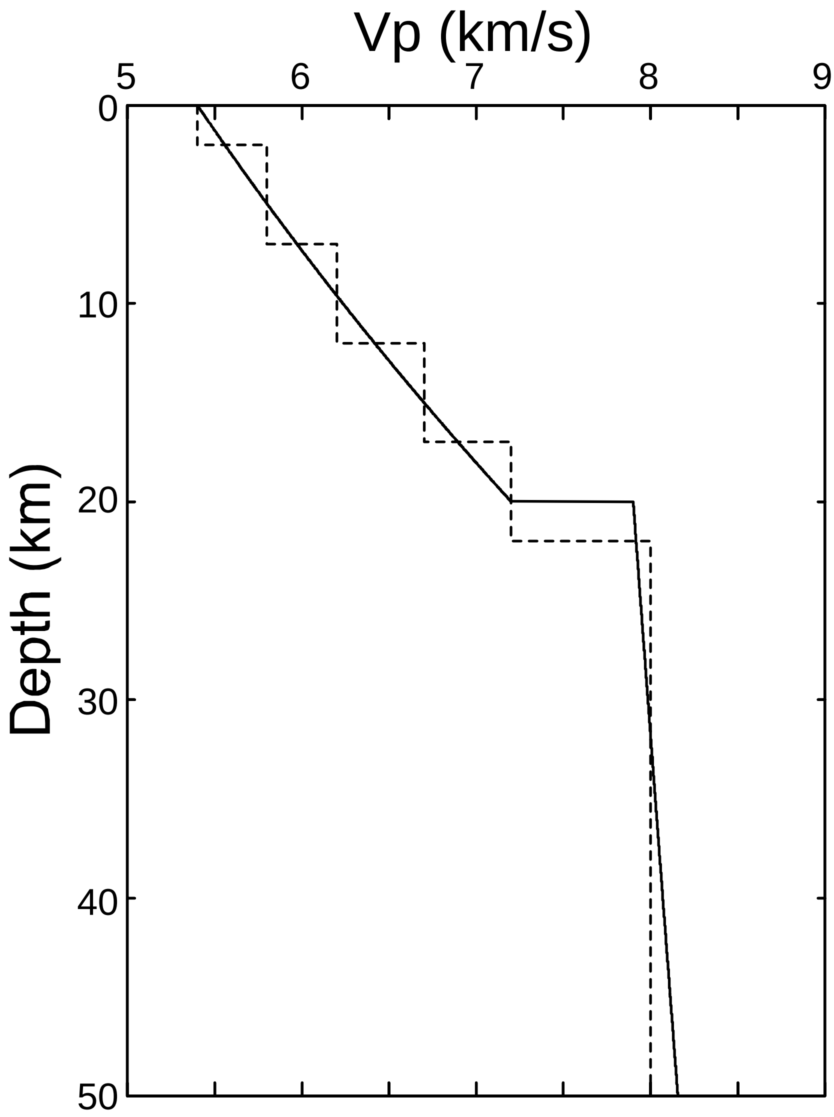

Fig. 2 Vp structure models for the conventional hypocenter determination using absolute travel time data (solid line) and for the double-difference location method (dashed line). In both of the hypocenter determinations, Vp/Vs is assumed to be 1.73.

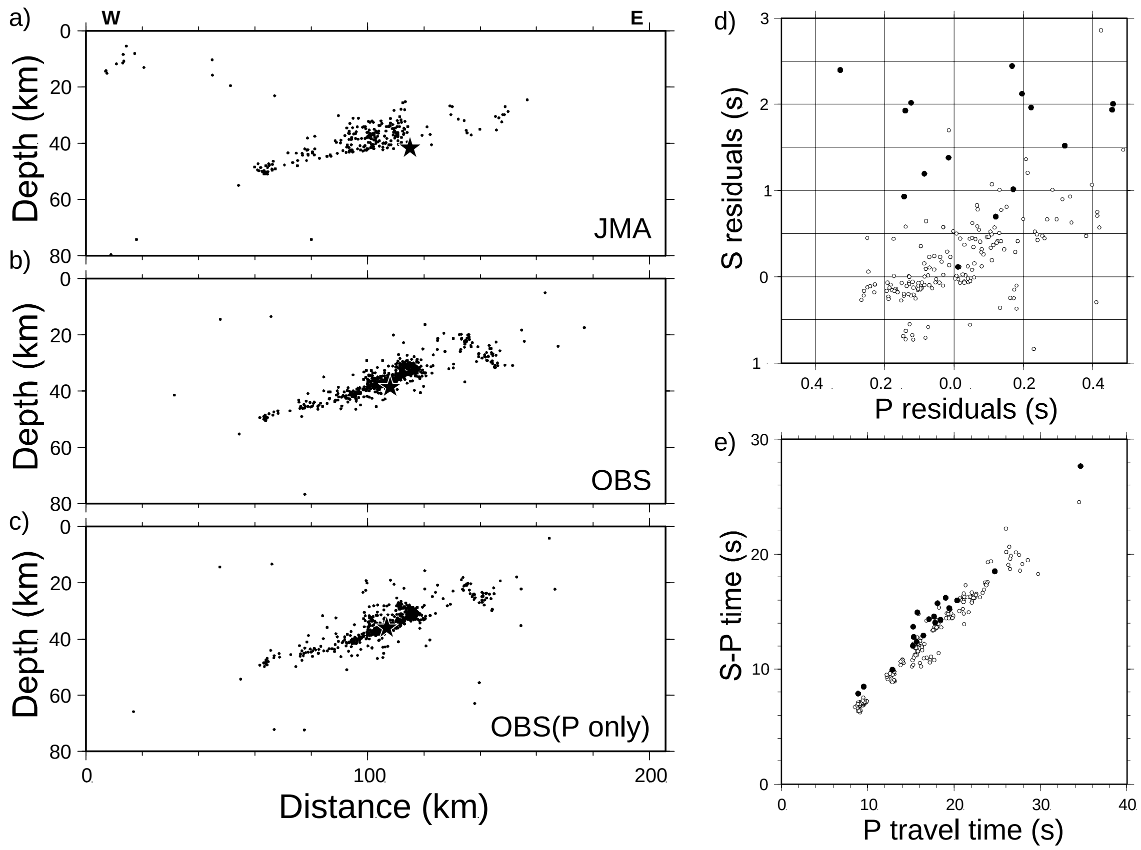

Fig. 3 Focal depth distribution of the mainshock and aftershocks of the 2005 earthquake (a-c) and a diagram showing relation between travel time residuals for P and S waves (d). a) Focal depth distribution determined by JMA. Star and dots are for mainshock and aftershocks. b) Focal depth distribution determined by this study. Both P and S wave arrival times are used. c) Focal depth distribution using only P wave arrival time data. d) Relation between travel time residuals for P and S wave at each of the onshore seismic stations. Solid symbols are for the mainshock and open symbols are for aftershocks whose epicenters are located within 2 km from the mainshock.

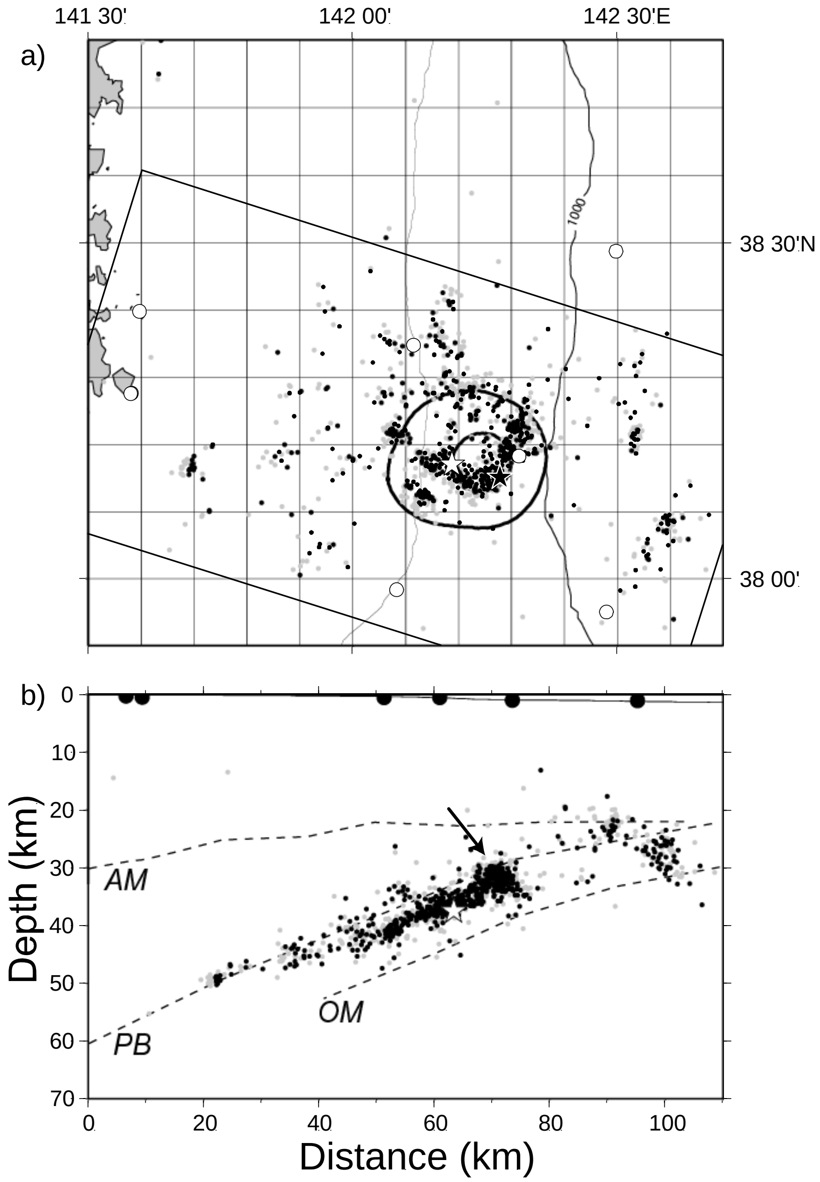

Fig. 4 Relocated hypocenter distribution of the mainshock and aftershocks of the 2005 Off Miyagi Earthquake. Gray and black dots are determined by the conventional inversion and the DD location method, respectively. White star is the location of the mainshock hypocenter. a) Epicenter distribution. Open circles are the locations of seismic stations. Black star indicates the epicenter of the mainshock according to the JMA catalogue. Thick contours show coseismic slip distribution by Yaginuma et al. (2005) with an interval of 0.3 m. b) Focal depth distribution of the earthquakes in the rectangle shown in a). Solid circles are locations of the seismic stations projected onto the cross section. Dashed lines are major layer boundaries estimated by the seismic experiment (Ito et al., 2005). AM: Arc's Moho. PB: Plate Boundary, OM: Oceanic crust's Moho. An arrow points the position of the northeast-southwest trending arm of the L-shape cluster.