Revisiting the three M∼7 Miyagi-oki earthquakes in the 1930s: possible seismogenic slip on asperities that were re-ruptured during the 1978 M=7.4 Miyagi-oki earthquake

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Hypocenters of main shocks and aftershocks of the 1933 M=7.1, 1936 M=7.4, 1937 M=7.1 and 1978 M=7.4 Miyagi-oki earthquakes are relocated using *S-P* times reported in the Seismological Bulletin of the Japan Meteorological Agency (JMA) and those re-read from original smoked-paper seismograms observed at the Mizusawa station of the National Astronomical Observatory of Japan (NAOJ) and the Mukaiyama station of Tohoku University. In order to reduce the error caused by inaccuracies of the arrival times and the small number of seismic observation stations, we determined the hypocenters by using a grid search method that assumed that the events occurred at the boundary between the subducting Pacific plate and the overriding plate. The main shock epicenters of these four earthquakes were determined to be close to each other, while the distributions of their aftershocks seem to disperse on the upper boundary of the Pacific plate. These distributions show that aftershock areas of the 1933, 1936 and 1937 events partly overlap with that of the 1978 event and occupy its easternmost, central and westernmost portions, respectively. This result suggests that the 1933, 1936 and 1937 events possibly ruptured a part of the source area of the 1978 event, i.e., its eastern, central and western portions, respectively.
Key words: Miyagi-oki earthquake, asperity, interplate earthquake, subduction zone, smoked-paper seismogram.

1. Introduction

An M=7.2 interplate earthquake occurred in the Miyagi-oki region, northeastern Japan, at 11:46 (JST) on August 16, 2005. Historical and seismic records indicate that large interplate earthquakes with magnitudes of ∼7.5 have occurred repeatedly in this region with a recurrence interval of ∼37 years since 1793 (The Headquarters for Earthquake Research Promotion, MEXT, Japan, 2001). The previous Miyagi-oki earthquake occurred on June 12, 1978, with magnitude of 7.4. Okada *et al.* (2005) estimated the locations of the main shocks and aftershocks of the 2005 M=7.2 and 1978 M=7.4 events using a double difference hypocenter locations algorithm (Waldhauser and Ellsworth, 2000). Their study revealed that the aftershock area of the 2005 earthquake partly overlapped the southern/southeastern area of the 1978 aftershock zone. The coseismic slip area of the 2005 event also partly overlapped with that of the 1978 event, suggesting that the 2005 event ruptured only part of the source area of the 1978 event.

The Miyagi-oki earthquake that occurred before the 1978 M=7.4 earthquake took place on November 3, 1936 and had a magnitude of 7.4 (The Headquarters for Earthquake Research Promotion, MEXT, Japan, 2001). Yamanaka and Kikuchi (2004) estimated the coseismic slip area of this event by inverting the seismic waveform data observed at two nearby stations and found that it was located adjacent to an area southeast of the source area of the 1978 event. Tanioka and Hasegawa (2005) recently reported that the seismic moment of the 1936 event was 0.68×10^{20} Nm (M_w=7.2) based on tsunami waveform inversions. Moreover, a pair of M=7.1 earthquakes occurred on June 19, 1933 and July 27, 1937, respectively, that ruptured regions adjacent to the 1936 event.

The Miyagi-oki sequence occurred in the context of similar sequences of interplate earthquakes off the east coast of northeastern Japan. Recent research suggests the existence of numerous asperities on the plate boundary in this region (Nagai *et al.*, 2001; Okada *et al.*, 2003; Yamanaka and Kikuchi, 2003, 2004; Matsuzawa *et al.*, 2004; Hasegawa *et al.*, 2005). These asperities are distributed in patches surrounded by regions of stable sliding area. A seismic slip in these regions results in the accumulation of stress at the asperities. Asperities cause large slips upon failure, leading to earthquakes when the accumulated stress reaches the strength limit of the asperity. Consequently, the relative locations of the coseismic slip areas of these 1930s' earthquakes and those of the 1978 earthquake may offer a key to understanding of the mechanism involved in the occurrence of interplate earthquakes and to predicting the location and the size of the next Miyagi-oki earthquake. However, pre-

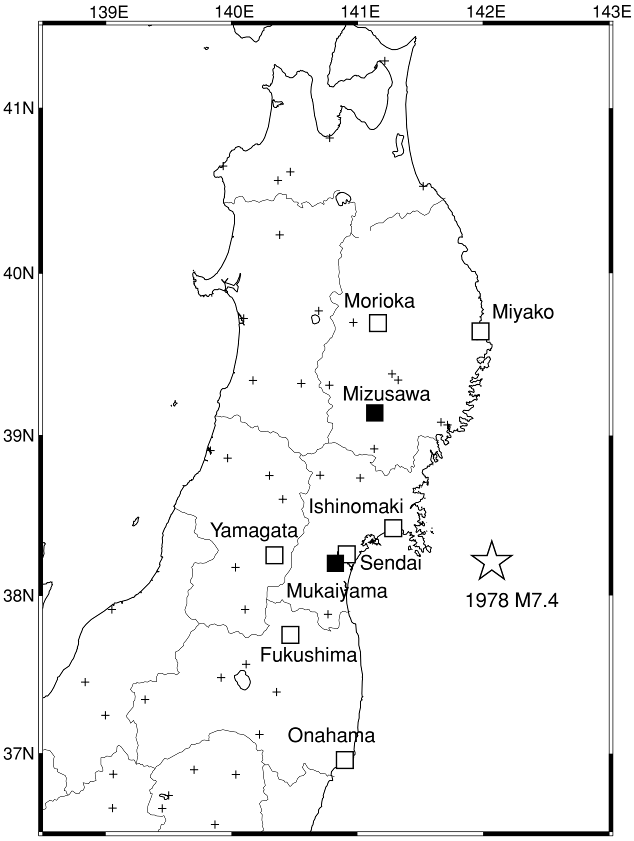

Fig. 1. Map showing the observation stations used in the present study. Stations of the Japan Meteorological Agency (JMA) are shown as open squares. Solid squares denote the Mukaiyama station, Tohoku University and the Mizusawa station (National Astronomical Observatory), whose original smoked-paper seismograms are re-read in this study. Crosses show the JMA stations, whose data are not used in the present study. The star denotes the epicenter of the 1978 event.

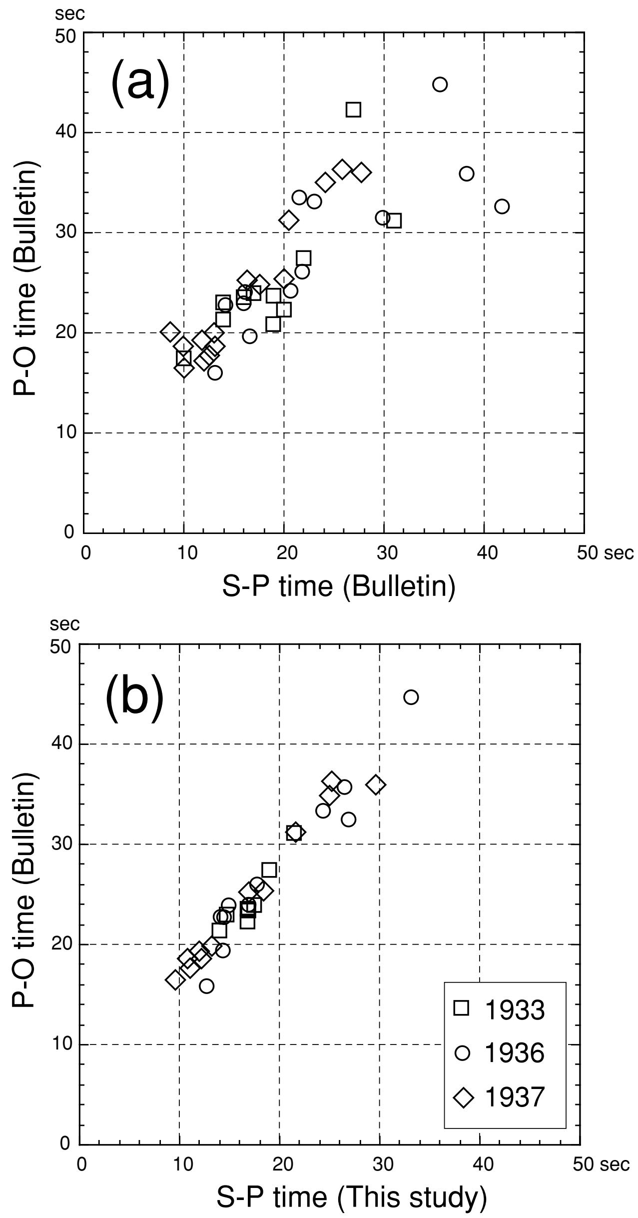

Fig. 2. Distribution of P-O times and S-P times observed at Mizusawa station for aftershocks of the 1933, 1936 and 1937 Miyagi-oki earthquakes. Squares, circles and diamonds denote arrival time data of aftershocks of the 1933, 1936 and 1937 earthquakes, respectively. (a) P-O times plotted against S-P times using those listed in the bulletin of Mizusawa station. (b) P-O times plotted against S-P times using those re-picked from the original smoked-paper seismograms used in this study. Origin times ($=O$) are determined by the JMA location procedure and are listed in the Seismological Bulletin of the JMA.

cise estimation of the coseismic slip areas for these 1930s' events is not easy because of the lack of sufficient waveform data. Instead, we investigated the distributions of the aftershocks of the 1930s' earthquakes and compared these with those of the 1978, assuming that the aftershock areas nearly correspond with the source areas of these main shocks.

2. Data

Arrival times for P- and S-waves for previous earthquakes are reported in the Seismological Bulletin of the Japan Meteorological Agency (JMA). We initially tried to determine the hypocenters of previous Miyagi-oki earthquakes from these arrival times. There are some questions as to the accuracy of the time of the previous arrival time data because of the seismological observation system at that time. Consequently, S-P time data alone were used for locating hypocenters in this study. The locations of the JMA stations, whose S-P times were used in the present study, are shown by open squares in Fig. 1.

In this study, S-P times at Mukaiyama station, Tohoku University and those at Mizusawa station, NAOJ were re-picked from the original smoked-paper seismograms. The locations of Mukaiyama and Mizusawa stations are also shown as solid squares in Fig. 1. The relationship between P-O times and S-P times at Mizusawa station from aftershocks of the 1930s' Miyagi-oki earthquakes is shown in Fig. 2. The relation between P-O times and S-P times listed in the Bulletin of Seismological Observations at Mizusawa (The International Latitude Observatory of Mizusawa, 1984) is shown in Fig. 2(a). In comparison, the relationship between P-O times and S-P times re-picked on the east-west component of the Omori' seismograms used in the present study is shown in Fig. 2(b). A less scattered distribution of arrival times is clearly shown in Fig. 2(b); consequently, we adopted those S-P times at the Mizusawa station instead of those listed in the Seismo-

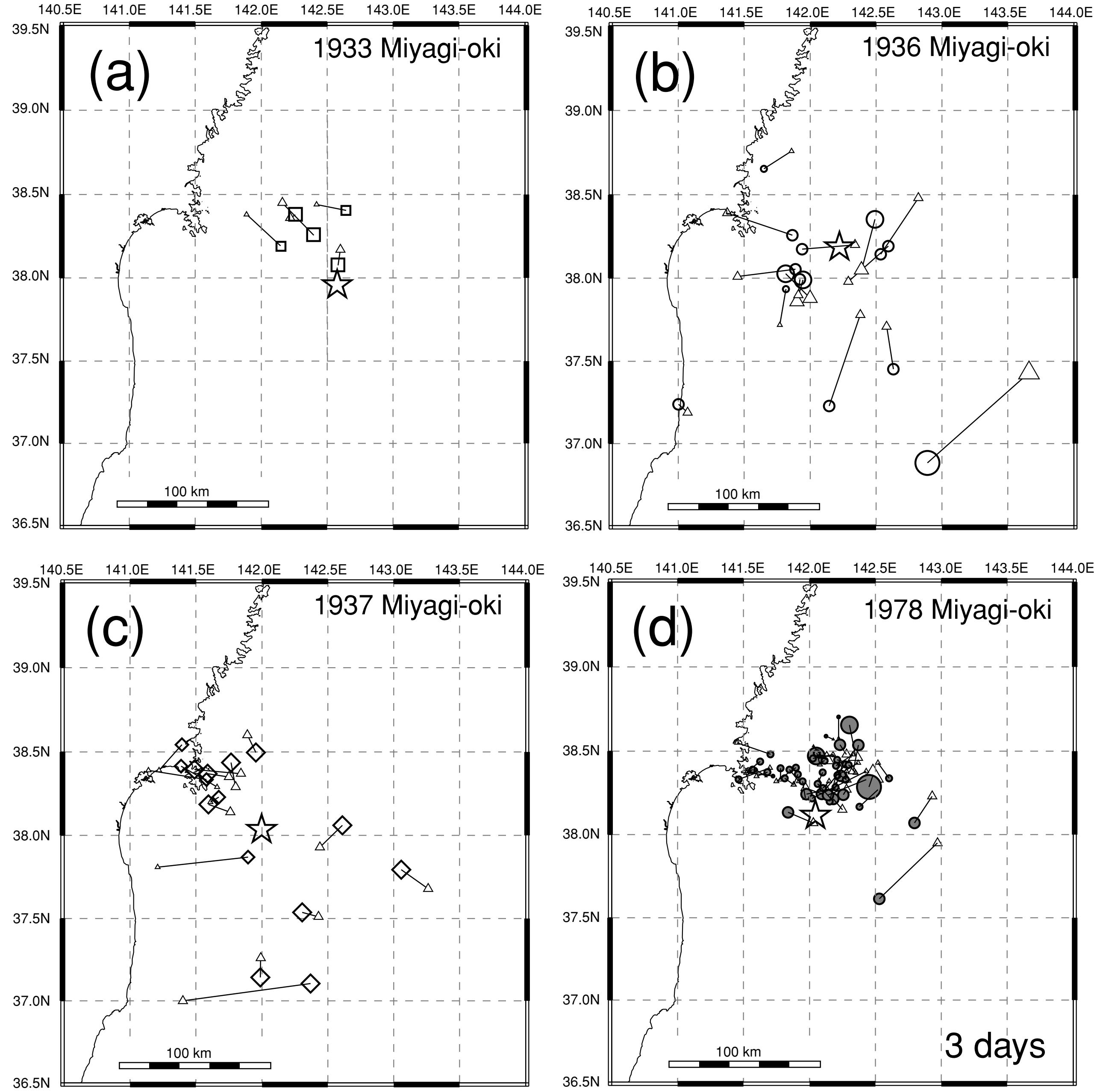

Fig. 3. Epicenter distribution of main shock and aftershocks. Stars denote the locations of the main shocks estimated from *S*-*P* times in this study. Triangles show the locations of aftershocks estimated by JMA. (a) Distribution of aftershocks of the 1933 earthquake within 1 month after the earthquake (squares). (b) Distribution of aftershocks of the 1936 earthquake within 1 month after the earthquake (open circles). (c) Distribution of aftershocks of the 1937 earthquake within 1 month after the earthquake (diamonds). (d) Distribution of aftershocks of the 1978 earthquake within 3 days after the earthquake (solid circles).

logical Bulletin of the JMA for locating hypocenters. *S*-*P* times on seismograms of the Mukaiyama station were also re-picked in the present study and used in locating hypocenters. Because we assume that three 1930s' Miyagi-oki earthquakes took place on the plate boundary, their focal depths are fixed by the depths of the Pacific plate at those locations. The location of the plate boundary is established from aftershock distribution determined by OBS observations conducted immediately following the occurrence of the 2005 Miyagi-oki earthquake (Hino *et al.*, 2005). In order to avoid errors caused by the small number of seismic observation stations, we determined hypocenters based on a 2-dimensional (2-D) grid search method by using *S*-*P* times. Grid intervals are 2 km. Theoretical *S*-*P* times are calculated based on the velocity model adopted in the routine procedure of the Tohoku University seismic network (Hasegawa *et al.*, 1978). In order to compare locations of aftershocks of the 1930s' events with those of the 1978 one, we relocate these later events using this same procedure.

3. Epicenter Distribution of the Main Shocks and Aftershocks

Epicenters of the main shocks and aftershocks are estimated from the 2-D grid search method based on *S*-*P* times, assuming those events are interplate earthquakes. The number of valid *S*-*P* times generally varies with the magnitude

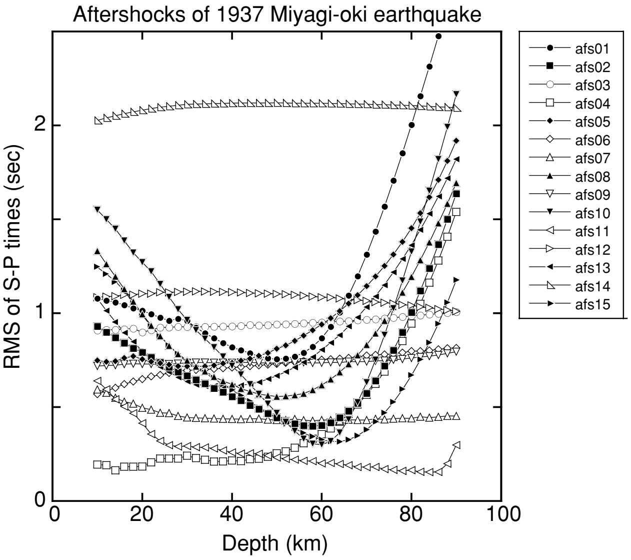

Fig. 4. RMS residuals of S-P times of aftershocks of the 1937 M=7.1 earthquake estimated by the 3-D grid search method. Solid and open symbols denote aftershocks with distinct and obscure minimum values, respectively. Seven aftershocks (afs 1, 2, 5, 8, 10, 13 and 15) are well constrained by the 3-D grid search.

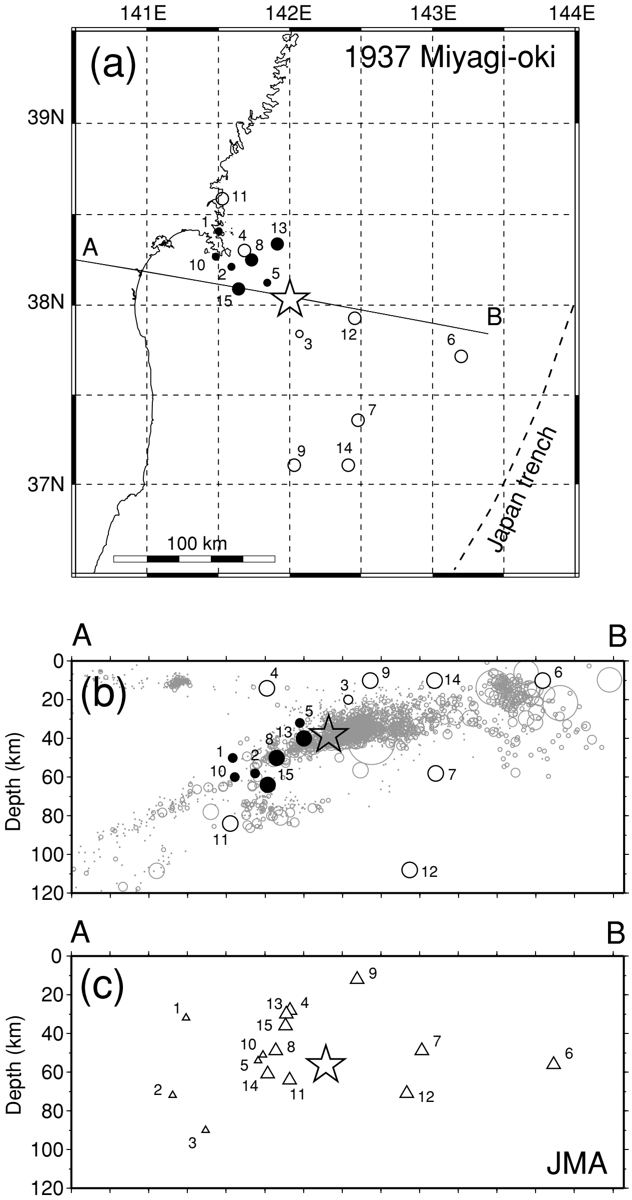

Fig. 5. Hypocenter distribution of aftershocks the 1937 M=7.1 earthquake. Numbers are chronological aftershock numbers. (a) Map showing relocated epicenters. Solid and open circles denote epicenters of aftershocks with distinct and obscure minimum RMS residuals of S-P times, respectively. The star and line AB show the locations of the main shock and cross section in Fig. 5(b), respectively. (b) Depth distribution of relocated aftershocks. Gray circles denote hypocenters of microearthquakes determined by JMA. (c) Depth distribution of the main shock and aftershocks listed in the Seismological Bulletin of the JMA.

of the event. We estimated epicenters of the aftershocks from at least four of S-P time data sets.

The epicenters that we obtained of the main shocks and aftershocks of the three 1930s' events and the 1978 event are shown in Fig. 3. Stars indicate the epicenters of the main shocks, while squares, open circles, diamonds and solid circles indicate the epicenters of aftershocks of the 1933, 1936, 1937 and 1978 events, respectively. Open triangles show the epicenters of aftershocks listed in the Seismological Bulletin of the JMA. Aftershocks of the 1930s' events that occurred within 1 month after the main shock occurrence are shown in Fig. 3(a)–(c). In the case of the 1978 event, aftershocks that occurred within 3 days are shown in Fig. 3(d). Assuming that those M∼7 earthquakes are interplate earthquakes, focal depths of the 1937 earthquakes should be deeper than those of the 1936 and 1933 earthquakes. This inference is very consistent with the no/very small tsunami caused by the 1937 earthquake and the very distinct tsunami caused by the 1936 earthquake (Tanioka and Hasegawa, 2005).

Kanamori *et al.* (2006) investigated the teleseismic waveforms of the 1930s', 1978 and 2005 Miyagi-oki earthquakes and showed that surface wave amplitudes of the 1937 M=7.1 event recorded at teleseismic stations were smaller than those of the other Miyagi-oki events. They also identified a possible depth phase and suggested that the 1937 M=7.1 event was not an interplate earthquake but an intraplate one. Moreover, they showed that two M∼7 intraplate earthquakes occurred in the neighborhood of this region on February 20, 1978 and May 26, 2003.

To investigate this possibility we relaxed our assumption that the 1937 M=7.1 event was interplate, and initiated a 3-D grid search in an effort to better constrain the hypocenters of the 15 aftershocks of the 1937 M=7.1 event. Grid intervals are also 2 km in both the horizontal and vertical directions. The relationship between the RMS residuals of S-P times and the trial focal depths of the aftershocks are shown in Fig. 4. The solid symbols denote aftershocks with distinct depth minima in RMS residuals of S-P times, indicating that these hypocenters are well determined; open symbols denote aftershocks with obscure minima in RMS residual of S-P times, indicating that these hypocenters are not well constrained. Solid and open circles in Fig. 5 denote the locations of aftershocks of the 1937 event with distinct and obscure minima in RMS residuals of S-P times, respectively. Numbers and stars denote the chronological aftershock number and location of the main shock (see

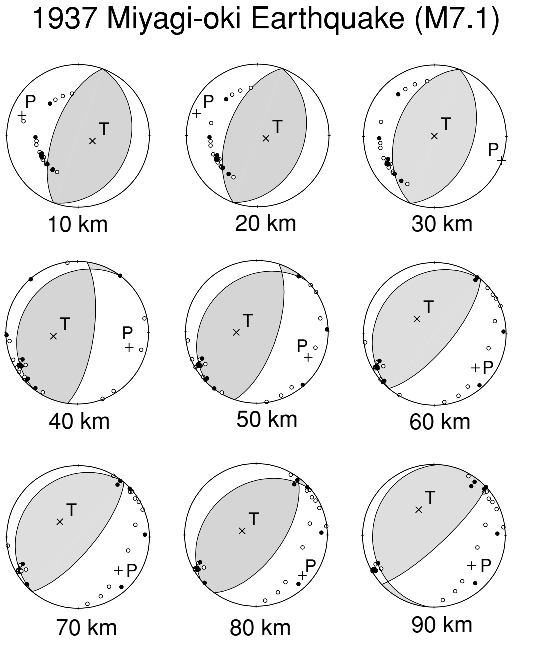

Fig. 6. Focal mechanism variations of the 1937 M7.1 earthquake. Focal mechanisms with focal depths from 10 km down to 90 km are shown by an equal area projection on a lower focal hemisphere. Low-angle thrust fault type mechanisms are revealed in the case of focal depths deeper than 40 km.

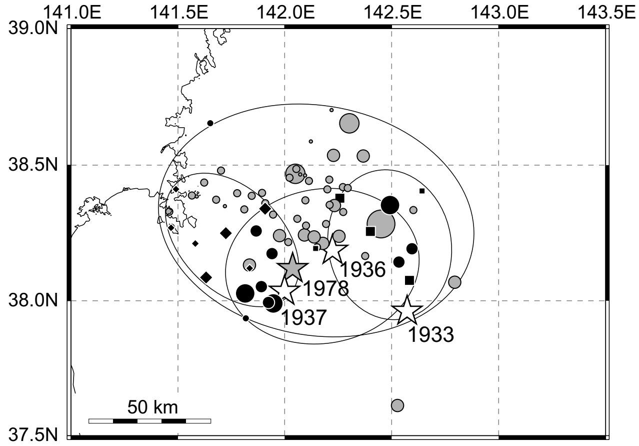

Fig. 7. Epicenter distribution of main shocks and aftershocks of the previous M∼7 Miyagi-oki earthquakes. Solid squares, solid circles, solid diamonds and gray circles denote epicenters of aftershocks of the 1933, 1936, 1937 and 1978 earthquakes, respectively. Estimated aftershock areas of these earthquakes are roughly encircled by ellipses. The combined aftershock area of the three 1930s' earthquakes is in close agreement with that of the 1978 earthquake.

Fig. 3(c)). Gray circles show the locations of recent microearthquakes determined by JMA. The aftershocks of the 1937 event with well-determined focal depths took place near the upper boundary of the Pacific plate. Consequently, the 1937 M=7.1 event is probably an interplate earthquake. The triangles in Fig. 5(c) show the hypocenters of the aftershocks of the 1937 event listed in the Seismological Bulletin of the JMA.

Typical focal mechanisms of interplate earthquakes are low-angle thrust faults, and the mechanisms of intraplate events are down-dip compressional (e.g. Hasegawa *et al.*, 1978). The focal mechanism of the 1937 M=7.1 earthquake is estimated from initial motions of the P-waves. We then varied the assumed focal depth from 10 to 90 km. Variations in the focal mechanisms are shown in Fig. 6 by an equal area projection on a lower focal hemispheres. Down-dip compressional fault types are consistent with first motions for the case of very shallow assumed focal depths only, and in any case would be inconsistent with focal mechanism characteristics in this region (Hasegawa *et al.*, 1978). Low-angle thrust fault type mechanisms, which are a typical focal mechanism for interplate earthquakes, are consistent with first motions, even when the assumed focal depths are changed from 40 to 60 km.

4. Discussion

The aftershock distributions of the 1930s' and 1978 Miyagi-oki earthquakes were investigated using a grid search method based on S-P times. Figure 7 shows the main shock and aftershock distributions of the four M∼7 Miyagi-oki earthquakes. Aftershocks of the 1933, 1936 and 1978 events are relocated by the 2-D grid search method (Fig. 3(a), (b), (d)), and aftershocks of the 1937 event are relocated by the 3-D grid search method to test the possibility that this event was not an interplate earthquake (Fig. 5). The aftershock areas of all these M∼7 earthquakes are estimated from their aftershock distributions and are encircled by ellipses in Fig. 7. The estimated aftershock areas of the three 1930s' events are partly overlapped by the eastern, southern and western parts of the 1978 rupture, respectively. The combined aftershock area of the three 1930s' earthquakes is in close agreement with that of the 1978 earthquake.

The moment magnitude of the 1936 event estimated from tsunami waveform inversion (Tanioka and Hasegawa, 2005) is M_w=7.2, which is significantly smaller than M_{JMA}=7.4 listed in the Seismological Bulletin of the JMA. One of the possible interpretations of the present study is that the 1978 M=7.4 earthquake involved the rupture of at least three major asperities that were adjacent to one another, whereas the 1933, 1936 and 1937 earthquakes were caused by separate ruptures of each asperity in the Miyagi-oki region.

Okada *et al.* (2005) relocated the main shocks and aftershocks of the 1978 M=7.4 and 2005 M=7.2 Miyagi-oki earthquakes by the double-difference hypocenter location algorithm, revealing that the 2005 event took place in the southern/southeastern part of the source area of the 1978 event. The moment magnitude of the 1936 event estimated from tsunami data is M_w=7.2, which is almost the same as that of the 2005 M=7.2 event. A comparison of the location of the source area and the magnitude of the 1936 event with those of the 2005 event suggests the possibility that the 2005 event may have been a re-rupture of the asperity that caused the 1936 event in the past.

On the basis of these results, it may be said that there are several asperities offshore of Miyagi Prefecture and that those asperities can, on occasion, rupture in one large event: (e.g. the 1978 Miyagi-oki earthquake) and can, at other times, rupture separately (e.g. during the sequence of events in the 1930s). In the case of the 2005 earthquake, only a southern/southeastern asperity may have ruptured on August 16, 2005. There is room for further investigation on the amounts of coseismic slip distributions of the 1930s' M∼7 earthquakes. If we knew the precise locations of asperities that caused the 1930s' and 1978 earthquakes, we would be a step closer to furthering our understanding of the mechanism of interplate earthquakes.

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