Revisit to the 1930s' three Miyagi-oki earthquakes with magnitude more than 7 : Possible rupturing of asperities that caused the 1978 M7.4 Miyagi-oki earthquake

Norihito Umino[1], Toshio Kono[1], Tomomi Okada[1], Junichi Nakajim[1], Toru Matsuzawa[1], Naoki Uchida[1], Akira Hasegawa[1], Yoshiaki Tamura[2] and Gen Aoki[3]

[1]Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-8578, Japan

[2]National Astronomical Observatory of Japan, Hoshigaoka 2-12, Mizusawa, Iwate 023-0861, Japan

[3]Sendai District Meteorological Observatory, Gorin 1-3-15, Miyagino-ku, Sendai, Miyagi 983-0842, Japan

Hypocenters of main shocks and aftershocks of the 1933 M7.1, 1936 M7.4, 1937 M7.1 and 1978 M7.4 Miyagi-oki earthquakes are relocated by using S-P times reported in the Seismological Bulletin of the Japan Meteorological Agency and those re-read in original smoked-paper seismograms observed at Mizusawa station of National Astronomical Observatory of Japan (NAOJ) and at Mukaiyama station of Tohoku University. In order to reduce the error caused by inaccuracy of the time and insufficiency of the number of seismic observation stations, we tried to determine hypocenters by using a grid search method assuming that those events occurred at the boundary between the subducting Pacific plate and the overriding plate. Main shock epicenters of these four earthquakes are determined close to each other, meanwhile distributions of their aftershocks seem to disperse on the upper boundary of the Pacific plate. Their distributions show that aftershock areas of 1933, 1936 and 1937 events partly overlap with that of the 1978 event and occupy its easternmost, central and westernmost portions, respectively. This suggest 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.

1. Introduction

An M7.2 inperplate earthquake occurred in the Miyagi-oki region, northeastern Japan, at 11:46 on August 16, 2005. In this Miyagi-oki region, large interplate earthquakes with magnitude of ~7.5 have occurred repeatedly at a recurrence intervals of ~37 yrs (The Headquarters for Earthquake Research Promotion, MEXT, Japan, 2001). The previous Miyagi-oki earthquake occurred on June 12, 1978, with magnitude 7.4. Okada et al. (2005) estimated locations of the main shocks and aftershocks of the 2005 M7.2 and 1978 M7.4 events using a double difference hypocenter locations algorithm (Waldhauser and Ellsworth, 2001). They revealed that the aftershock area of the 2005 earthquake is partly overlapped with the southern/southeastern part of that of the 1978 event. Coseismic slip area of the 2005 event is also partly overlapped with that of the 1978 event, suggesting that the 2005 event ruptured a part of the source area of the 1978 event.

The second previous Miyagi-oki earthquake occurred on November 3, 1936 with magnitude 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 seismic waveform data observed at two nearby stations. It was adjacently located to the southeast of the source area of the 1978 event. Recently Tanioka and Hasegawa (2005) estimated a seismic moment of the 1936 event as to be 0.68×10^{20} Nm (M_w7.2) from tsunami waveform inversions. Moreover, two M7.1 earthquakes occurred on June 19, 1933 and July 27, 1937 in adjacent regions of the 1936 event.

Recent research on interplate earthquakes east off northeastern Japan suggest the existence of 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). Asperities are distributed in patches surrounded by stable sliding areas and aseismic slip in the surrounding stable sliding areas results in the accumulation of stress at the asperities. Asperities cause large slip upon failure, leading to earthquakes when the accumulated stress reaches the strength limit of the asperity, Consequently, relative locations of the coseismic slip areas of these 1930s' earthquakes and that of the 1978 earthquake offer the key to understanding of the mechanism of occurrence of interplate earthquakes and to predicting the location and the size of the next Miyagi-oki earthquake. However, precise 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 distribution of aftershocks of the 1930s' earthquakes and compared with those of the 1978's, assuming that the aftershock area nearly corresponds with the source area of the main shock.

2. Data

Arrival times of P- and S-waves for previous earthquakes are available in the Seismological Bulletin of the Japan Meteorological Agency (JMA). We tried to estimate hypocenters of the previous Miyagi-oki earthquakes from these P- and S-wave arrival times. There is some questions as to 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 are used for locating hypocenters in this study. Locations of observation stations of JMA, whose S-P times are used in locating hypocenters, are shown by open squares in Fig.1.

S-P times at Mukaiyama station, Tohoku University and those at Mizusawa station, NAOJ are re-picked on the original smoked-paper seismograms in this study. Locations of Mukaiyama and Mizusawa stations are also shown by solid squares in Fig.1. Relation between P-O times and S-P times, i.e., Wadati's diagram, at Mizusawa station from aftershocks of the 1930s' Miyagi-oki earthquakes are shown in Fig.2. The Wadati's diagram at Mizusawa based on arrival times listed in the Bulletin of Seismological Observations at Mizusawa (The International Latitude Observatory of Mizusawa, 1984) is shown in Fig.2 (a). On the other hand, the Wadati's diagram based on the arrival times re-picked in the present study is also shown in Fig.2 (b). Less scattered distribution of arrival times are clearly shown in Fig.2 (b); consequently, we adopted those S-P times at Mizusawa station instead of those listed in the Seismological Bulletin of the JMA for locating hypocenters. Addition of S-P time data at Mukaiyama station re-picked in the present study is also contributed to hypocenter locations.

Assuming that those previous Miyagi-oki earthquakes took place on the plate boundary, focal depths of them and their aftershocks are fixed to be on the surface of the Pacific plate there. Location of the plate boundary is deduced from aftershock distribution determined by OBS observation conducted just after the occurrence of the 2005 Miyagi-oki earthquake (Hino et al., 2005). In order to avoid errors caused by insufficiency of the number of seismic observation stations, we tried to determine hypocenters based on a grid search method by using S-P time data. Grid intervals are 2 km both in horizontal and vertical directions. 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).

3. Epicenter distribution of the main shocks and aftershocks

Epicenters of the main shocks and aftershocks are estimated from the grid search method based on S-P times, assuming those events are the interplate earthquakes. Number of valid S-P time data generally varies with the magnitude of events. We estimated epicenters of the aftershocks from at least four of S-P time data.

Obtained epicenters of the main shocks and aftershocks of the three 1930s' events and the 1978 event are shown in Fig.3. Star shows the epicenter of the main shock. Squares, open circles, diamonds and solid circles denote 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. Since detectability of JMA network in 1930s' was very low, aftershocks that occurred within one month after the main shock occurrence are shown in Figs.3 (a),(b) and (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 more deeper than those of the 1936 and 1933 earthquakes. It is very consistent with no/very small tsunami caused by the 1937 earthquake and clear tsunami caused by the 1936 earthquake (Tanioka and Hasegawa, 2005).

Aftershock distribution of the 1930s' and 1978 Miyagi-oki earthquakes are revealed from the grid search method based on S-P time data. Figure 4 shows main shock and aftershock distribution of the four M~7 Miyagi-oki earthquakes. Aftershock areas of these M~7 earthquakes are estimated from their aftershock distributions and are encircled by ellipses in Fig.4. The estimated aftershock areas of the three 1930s' events are partly overlapped with the eastern, southern and western part of that of the 1978 event, 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_w7.2, which is significantly smaller than M_{JMA}7.4 listed in the Seismological Bulletin of the JMA. It is one of the possible interpretations of the present observation that the 1978 M7.4 earthquake involved the simultaneous rupture of at least three major asperities which are adjacent to one another, meanwhile the 1933, 1936 and 1937 earthquakes are caused by a rupture of each asperity in the Miyagi-oki region.

Okada et al. (2005) relocated the main shocks and aftershocks of the 1978 M7.4 and 2005 M7.2 Miyagi-oki earthquakes by the double-difference hypocenter location algorithm and revealed 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_w7.2, which is almost the same as that of the 2005 M7.2 event. 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 be caused by re-rupturing of the asperity that caused the 1936 event in the past.

From these results, it may de said that there are several asperities offshore of Miyagi Prefecture, and that those asperities rupture simultaneously at one time: sometime: e.g. at the occurrence of the 1978 Miyagi-oki earthquake, and rupture severally at other times: e.g. during the sequence of the 1930s' earthquakes. In the case of the 2005 earthquake, only a southern/southeastern asperity might have ruptured on August 16 2005. There is room for further investigation about the amounts of coseismic slip distributions of the 1930s' M~7 earthquakes. If we knew precise locations of asperities that caused the 1930s' and 1978 earthquakes, we would be a step closer to further understanding of the mechanism of interplate earthquakes.

Acknowledgment

This research was supported in part by the Research on the Tonankai and Nankai earthquakes from the Ministry of Education, Culture, Sports, Science and Technology of Japan. This work was also conducted as part of the 21st COE program, 'Advanced Science and Technology Center for the Dynamic Earth', at Tohoku University. This work was also partially supported by MEXT.KAKENHI (#17800002).

References

Hasegawa, A., N. Umino and A. Takagi, Double-planed structure of the deep seismic zone in the northeastern Japan arc, Tectonophysics, 47, 43-58, 1978.

Hasegawa, A., N. Uchida, T. Igarashi, T. Matsuzawa, T. Okada, S. Miura and Y. Suwa, Asperities and quasi-static slip on the subducting plate boundary east off Tohoku, NE Japan, SEIZE volume, Columbia Univ. Press., in press, 2005.

Hino, R., Y. Yamamoto, M. Nishino, T. Kanazawa, T. Yamada, K. Nakahigashi, K. Mochizuki, M.

Shinohara, G. Aoki, M. Tanaka, E. Araki, S. Kodaira, G. Fujie and Y. Kaneda, Hypocenter distribution of the 2005 Miyagi-oki earthquake and its aftershocks by OBS observation, PM02, Programme and abstracts the Seismological Society of Japan 2005, Fall meeting, 2005.

Matsuzawa, T., N. Uchida, T. Igarashi, T. Okada and A. Hasegawa, Repeating earthquakes and quasi-static slip on the plate boundary east off northeastern Honshu, Japan, Earth, Planets, and Space, 56, 803-811, 2004.

Nagai, R., M. Kikuchi and Y. Yamanaka, Comparative study on the source process of recurrent large earthquakes in Sanriku-oki region: the 1968 Tokachi-oki and the 1994 Sanriku-oki earthquakes, J. Seism. Soc. Japan, 54, 267-280.

Okada, T., T. Matsuzawa and A. Hasegawa, Comparison of source areas of M4.8+/-0.1 repeating earthquakes off Kamaishi, NE Japan – Are asperities persistent features?, Earth Planet Sc Lett, 213, 361-374, 2003.

Okada, T., T. Yaginuma, N. Umino, T. Kono, T. Matsuzawa, S. Kita and A. Hasegawa, The 2005 M7.2 Miyagi-oki earthquake, NE Japan: Possible Re-rupturing of one of asperities that caused the previous M7.4 earthquake, accepted in Geophys. Res. Lett, 2005.

Tanioka, Y., and Y. Hasegawa, Re-analysis of the source process of the 1936 Miyagi-oki earthquake using tsunami waveforms, P128, Programme and abstracts the Seismological Society of Japan 2005, Fall meeting, 2005.

The Headquarters for Earthquake Research Promotion, MEXT, Japan, Long-term evaluation of the Miyagi-Oki earthquake (in Japanese), http://www.jishin.go.jp/main/index.html, 2001.

The International Latitude Observatory of Mizusawa, Seismological observations at Mizusawa for the period between 1902~1967, pp379, 1984.

Waldhauser, F., and W. L. Ellsworth, A double-difference earthquake location algorithm: method and application to the Northern Hayward fault, Bull. Seism. Soc. Am., 90, 1353-1368, 2000.

Yamanaka, Y., and M. Kikuchi, Source process of the recurrent Tokachi-oki earthquake on September 26, 2003, inferred from teleseismic body waves, Earth Planets Space, 55, e21-e24, 2003.

Yamanaka, Y., and M. Kikuchi, Asperity map along the subduction zone in northeastern Japan inferred from regional seismic data, J. Geophys. Res., 109, 2003JB002683, 2004.

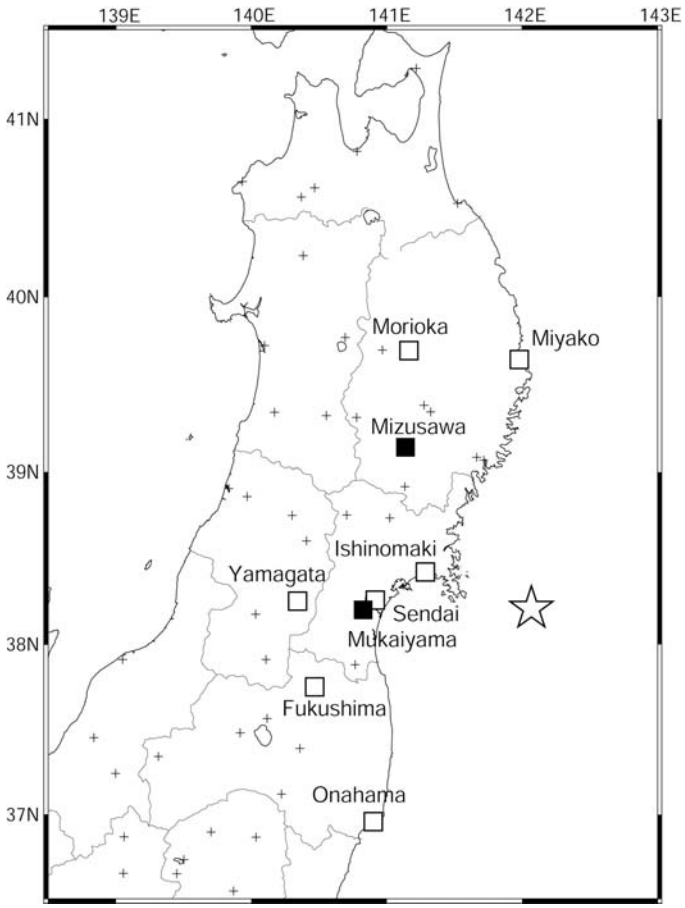

Fig.1. Map showing observation stations used in the present study. Stations of Japan Meteorological Agency (JMA) are shown by open squares. Solid squares denote Mukaiyama station, Tohoku University and Mizusawa station, National Astronomical Observatory, whose original smoked-paper seismograms are re-read in this study. Star denotes the epicenter of the 1978 event.

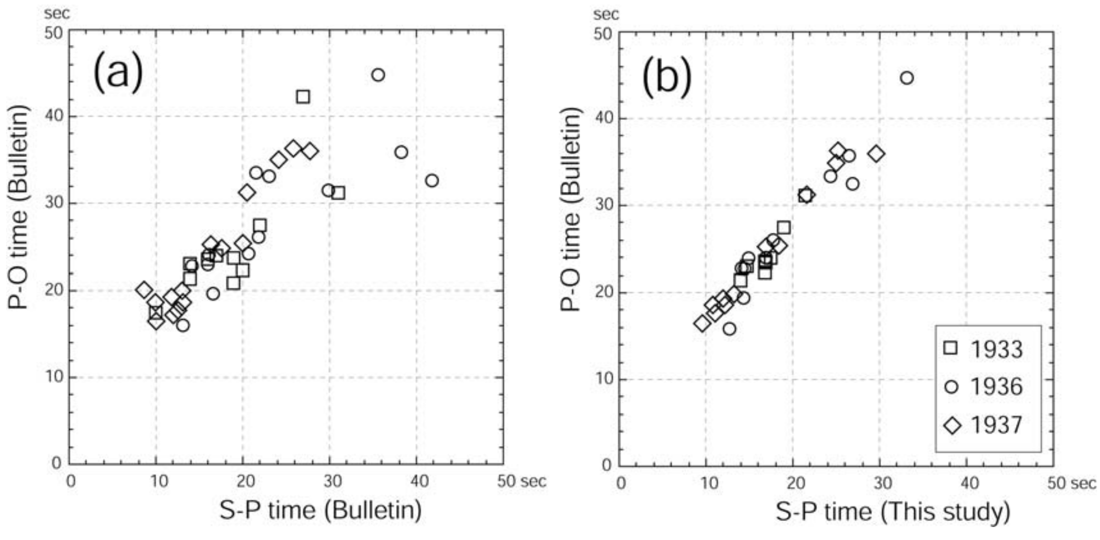

Fig.2. Wadati's diagrams at Mizusawa station for aftershocks of the 1933, 1936 and 1937 Miyagi-oki earthquakes. Squares, circles and diamonds denote arrival time data of aftershocks of the 1933, 1936 and 1937 earthquakes, respectively. (a) P-O times plotted against S-P times using those listed in the bulletin of Mizusawa station. (b) P-O times plotted against S-P times using those re-picked on the original smoked-paper seismograms in this study.

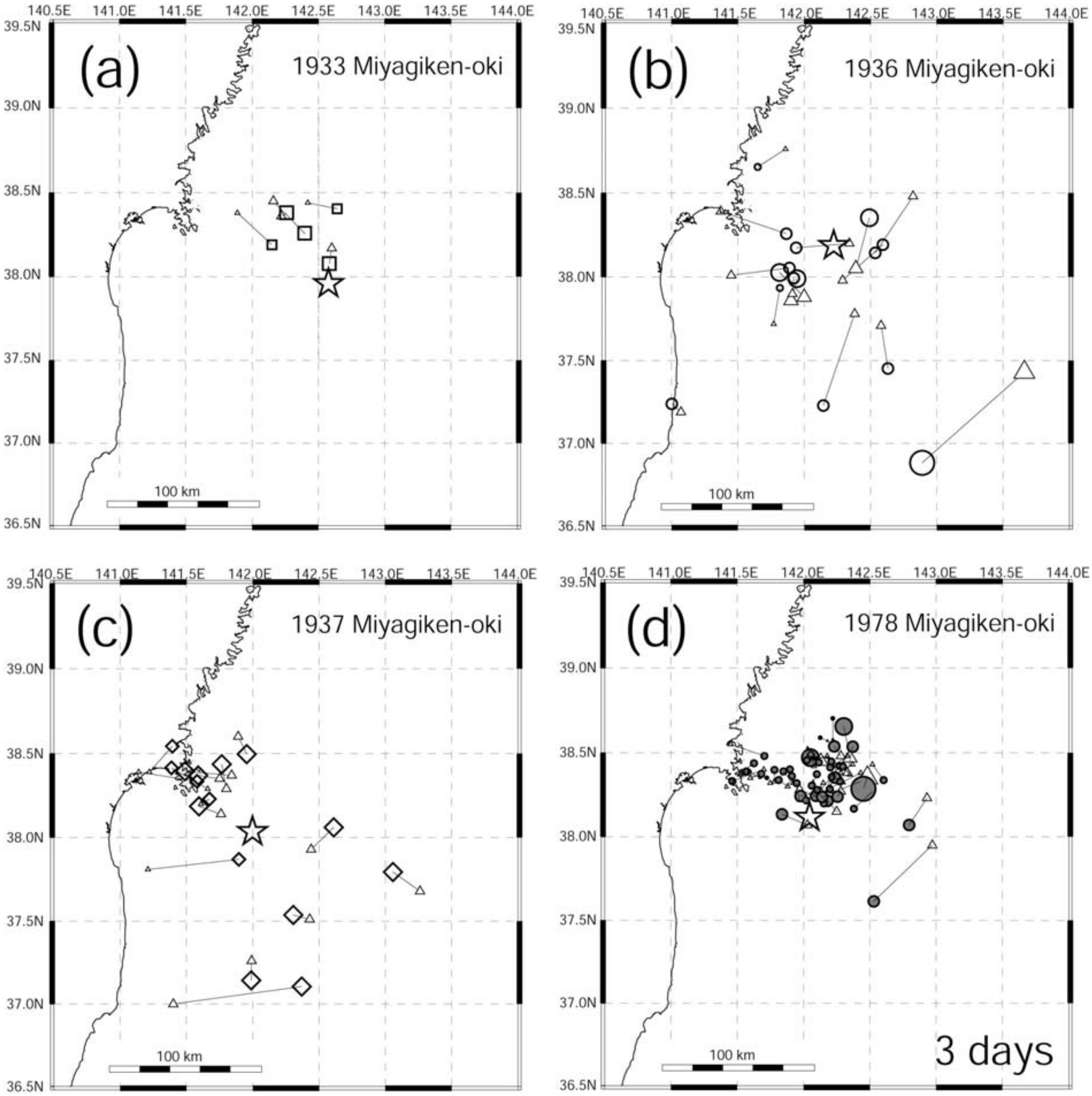

Fig.3. Epicenter distribution of main shock and aftershocks. Stars denote locations of the main shocks estimated from S-P times in this study. Triangles show locations of aftershocks estimated by JMA. (a) Distribution of aftershocks of the 1933 earthquake within one month (squares). (b) Distribution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

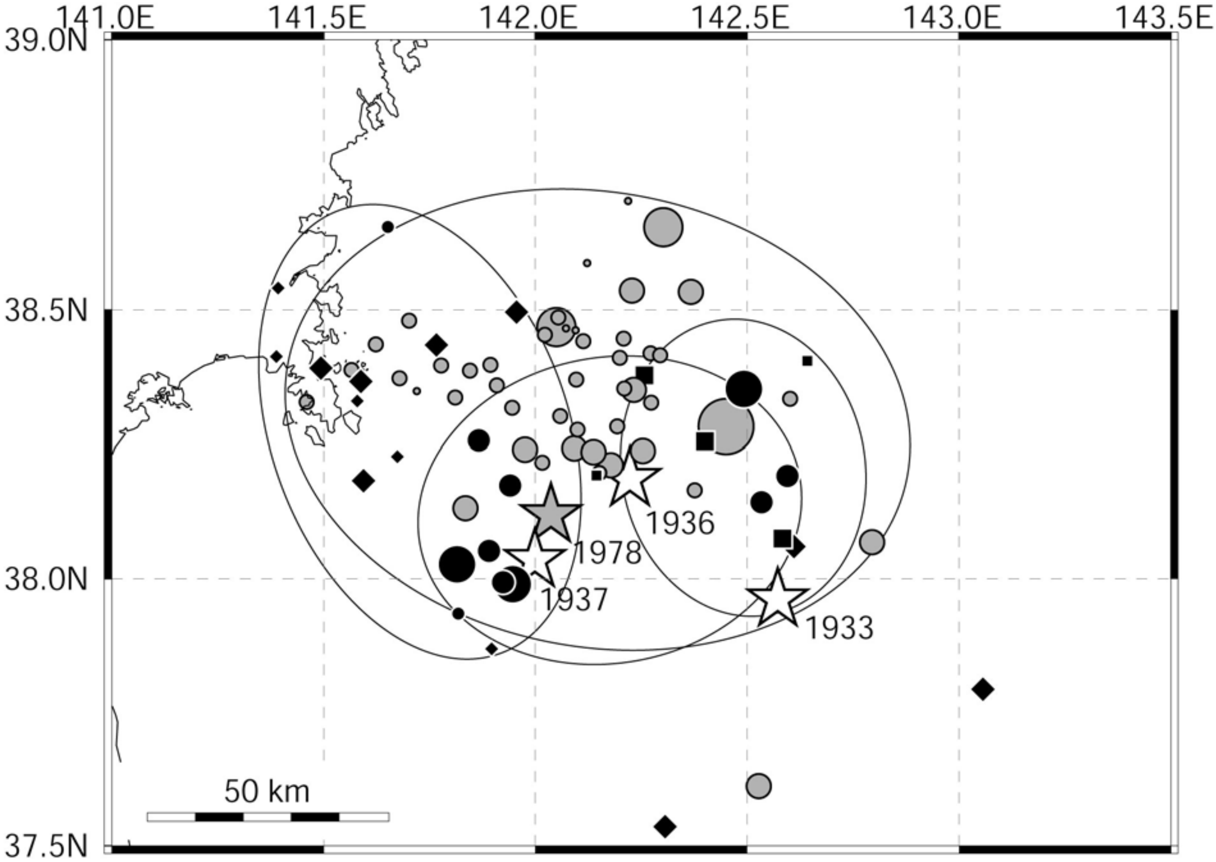

Fig.4. Epicenter distribution of main shocks and aftershocks of the previous M~7 Miyagi-oki earthquakes. Solid squares, solid circles, solid diamonds and gray circles denote epicenters of aftershocks of the 1933, 1936, 1937 and 1978 earthquakes, respectively. Estimated aftershock areas of these earthquakes are roughly encircled by ellipses. The combined aftershock area of the three 1930s' earthquakes is in close agreement with that of the 1978 earthquake.