Coseismic slip distribution of the 2005 off Miyagi earthquake (M7.2) estimated by inversion of teleseismic and regional seismograms

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A large earthquake (M7.2) occurred along the plate boundary off Miyagi Prefecture (Miyagi-Oki), northeastern Japan, on August 16, 2005. In this area, large earthquakes (～M7.5) have occurred repeatedly at intervals of about 37 years, and it has passed more than 27 years since the last event occurred. To estimate the relationship between this earthquake and the previous events, we determined coseismic slip distribution by this 2005 Miyagi-Oki earthquake by adopting the seismic waveform inversion method of Yagi *et al.*(2004) and compared with that of the previous 1978 Miyagi-Oki earthquake. We performed two cases of the inversions; inversion using only far-field seismograms, and that using far-field seismograms and local seismograms simultaneously. Both results show that large slip occurred near the hypocenter and rupture extended to the westward deeper portion. The rupture area of the 2005 event partly overlapped with the southeastern part of that of the 1978 event. This result possibly suggests that there exists plural asperities which cause the sequence of Miyagi-Oki earthquakes, and the 2005 event ruptured one of such asperities, although the previous 1978 event ruptured all the asperities at one time.

1. Introduction

A magnitude 7.2 interplate earthquake occurred at 11:46 on August 16, 2005 at a depth of approximately 40 km in the Miyagi-Oki region (offshore of Miyagi Prefecture), northeastern Japan. A maximum seismic intensity of just under 6 in JMA scale was observed in Kawasaki, Miyagi Prefecture, where considerable damage was reported, including 91 people injured and 1 house completely destroyed (according to the Fire and Disaster Management Agency, Ministry of Public Management, Home Affairs, Posts and Telecommunications).

Around the focal area of this event, interplate earthquakes with magnitudes of about 7.5 have repeatedly occurred at average intervals of approximately 37 years (Headquarters for Earthquake Research Promotion, 2001). The last Miyagi-Oki earthquake (M7.4) occurred on June 12, 1978, and caused major loss of life (28 deaths) and 1325 people injured. In recent years, a magnitude 7.1 intraslab earthquake occurred nearby on May 26, 2003 (Okada and Hasegawa, 2003). On July 26 of that same year, another magnitude 6.4 inland shallow crustal earthquake occurred (Okada *et al*., 2003; Umino *et al*., 2003), attracting considerable attention. Recent investigation on interplate earthquakes suggest the existence of asperities along the plate boundary east off northeastern Japan (Nagai *et al*., 2001; Okada *et al*., 2003; Yamanaka and Kikuchi, 2004; Igarashi *et al*., 2003; Matsuzawa *et al*., 2004; Uchida *et al*., 2005; Hasegawa *et al*., 2005). Back slip inversions of GPS data have shown that large back slip is distributed in the source area of the Miyagi-Oki earthquake (Suwa *et al*., 2004). Hasegawa *et al*. (2004) suggested that the July 26 M6.4 earthquake was due to the strong coupling in the asperity region of the Miyagi-Oki earthquakes, which causes compressive stress in the layer in which the July earthquake occurred. Thus, in recent years, scientists have come to believe that the plate boundary at the Miyagi-Oki earthquake asperities is strongly coupled.

Clarification of the relationship between this latest earthquake and the last Miyagi-Oki Earthquake, which occurred more than 27 years previous, is important in improving the modeling of Miyagi-Oki earthquakes, and therefore in disaster prevention. In the present paper, the rupture area in the 2005 Miyagi-Oki earthquake is estimated from the slip distribution determined by seismic waveform inversion of Yagi *et al*. (2004). Then, by comparison with the slip distribution of the Miyagi-Oki earthquake (Seno et al., 1980; Yamanaka and Kikuchi, 2004), the relationship between the 2005 Miyagi-Oki earthquake and the 1978 Miyagi-Oki earthquake is discussed.

2. Method

The waveform inversion method of Yagi *et al*. (2004) was used in the analysis. This method involves joint inversion of teleseismic body wave records and regional strong motion records. The former is suitable for determining the approximate extent of the rupture area, while the latter is suitable for determining the detailed rupture process. Use of the two sets of data provides the advantages of both in the analysis results.

In this research, the analysis was carried out in two stages. First, the existence of a broad (135 km×135 km) fault plane was assumed and the approximate rupture area was estimated by the waveform inversion of teleseismic body wave records. Next, to attempt a more detailed estimation of the rupture area, the assumed extent of the fault plane was reduced to 90 km×90 km, and joint inversion of resional strong motion records and teleseismic body wave records was performed. The assumed fault plane was divided into 9×9 small faults.

3. Data

Waveform data used in the analysis were obtained as follows. Teleseismic body wave records were those recorded by the Incorporated Research Institutions for Seismology (IRIS) at 24 broadband seismograph observation stations (Fig. 1(a)), and regional strong motion records were obtained at 3 basement strong motion observation stations of KiK-net, which is operated by the National Research Institute of Earth Science and Disaster Prevention. Data from an observation station of the Miyagi Prefecture Seismic Observation Network were also used (Fig. 1(b)). A 0.01–1.0 Hz bandpass filter was applied to the teleseismic body wave records, and a 0.1–0.5 Hz bandpass filter was applied to the regional strong motion records. Both records were converted to 5 Hz sampling displacement waveforms.

The epicentral location adopted, 38.144°N, 144.299°E, was that determined by Hi-net of the National Research Institute of Earth Science and Disaster Prevention. The depth of the hypocenter was taken to be 37 km, which was determined by using OBS data (Yamamoto *et al*., 2005; Hino *et al*., 2005).

For the geometrical parameters of the fault model, the AQUA-CMT values of the National Research Institute of Earth Science and Disaster Prevention were used: strike 198.2°, dip 22.2°. The assumed seismic velocity structure model is given in Table 1.

4. Results

4.1 Results assuming a broad fault plane

The seismic moments obtained are Mo = 8.8×10^{19} Nm and M_w = 7.2. The estimated slip distribution is shown in Fig. 2. The maximum slip is about 0.70 m, which occurred near the point where the main shock rupture initiated. The region of large slip during the earthquake extends in the direction of dip toward greater depth (the west side). The process by which rupture progresses in the direction of dip toward greater depth (particularly 4–8 s after the onset of rupture) can also be seen in the depiction of the rupture process in Fig. 3. The rupture stopped 12 s after the onset and then appears to have reactivated in the 13–15 s interval. This is seen on both sides of the strike. It is possible that this is due to deviation of the actual seismic velocity structure from the assumed structure model. The slip amount of this second portion of the rupture was also relatively small, only 0.23 m, which may not be important in reproduction of the overall rupture process. Accordingly, this delayed rupture is not discussed in the present paper.

A comparison of the theoretical waveform and the observed waveform is shown in Fig. 4. It is seen that the two agree reasonably well.

4.2 Results assuming a smaller fault surface

The obtained seismic moments are Mo = 8.9×10^{19} N m and Mw = 7.2. The distribution of slippage and a comparison between the theoretical waveforms and the observed waveforms are shown in Figs. 5 (a) and (b). Since this result is a result of joint inversion, the results for the 4 near strong motion observation stations are also shown. The slip distributions when the Moho thickness in the velocity structure model is varied are shown in Figs. 5 (c) and (d). In all of the slip distributions, relatively large slip occurs at the corners of the assumed fault plane. However, in Fig. 2, which shows an overall view of the rupture region, significant amounts of slip are not seen in these regions. For this reason, the slip around the hypocentral region that could not be reproduced is considered to have been pushed to the corners of the fault surface. This may be related to the assumed velocity structure model as in the case shown in section 4.1.

5. Discussion

5.1 Analysis assuming a broad fault plane

The final slip distribution in Fig. 2 and the rupture process shown in Fig. 3 suggest that following the main rupture in the vicinity of the hypocenter, rupture proceeded along the dip direction to greater depth. This implies that the rupture proceeded toward the west, which can be seen from the directional dependence of the original observed waveforms. For example, looking at the comparison between the theoretical waveforms and the observed waveforms in Fig. 4, at observation stations east and west of the hypocenter, the rise of the waveform of P wave differs in that the rise is sharp and spiked at the western observation stations, and gradual and angled at the east observation stations. The overall appearance of the waveforms depends greatly on the direction of the observation stations. It is therefore believed that the difference in waveforms is due to the directivity. From the fact that the waveform at the western observation stations is spiked, it can be said that the propagation of rupture toward the west is natural given the directional dependence of the waveform.

5.2 Analysis assuming a smaller fault plane

The slip distribution indicates that after the large slip in the vicinity of the hypocenter, rupture propagated in the direction of dip to greater depth (toward the west). Comparison with Figs. 5 (c) and (d) reveals that when the Moho is set deeper, the details of the slip distribution change. Thus, the slip distribution appears to be affected by variations in the velocity structure. However, the distributions have two features in common: the principal rupture occurs in the vicinity of the hypocenter, and the rupture propagates to the west. These features are also similar to those obtained from the results of analysis using only the teleseismic waveforms.

In the present inversion, the observed waveforms were not weighted equally. The east-west component in Tsuyama (TUYAM_ EW) was weighted less because when uniform weights were used, the waveform at the western observation stations could not be reproduced well. In manual adjustment to reproduce the spiked rise that played an important role in section 5.1, it was found that the problem was solved by decreasing the weight of the east-west component in Tsuyama. This is probably caused by a difference between the velocity structure in the vicinity of the Tsuyama observation station and that used in the present analysis.

5.3 Comparison with the 1978 M7.4 Miyagi-Oki earthquake

The relationship of the present earthquake to the 1978 Miyagi-Oki earthquake is discussed by comparing the results obtained from the analyses of the two earthquakes. Figures 6 (a) and (b) superimposes the slip distributions for the 1978 Miyagi-Oki earthquake (Yamanaka and Kikuchi, 2004) with those for the 2005 Miyagi-Oki earthquake and the respective aftershock distributions (Okada *et al*., 2005). Since the slip distribution for the 2005 event was obtained referring to the results of both the teleseismic waveform inversion and the joint inversion, the results are shown in two figures (Figs. 6 (a) and (b)). Normally, the joint inversion result (Fig. 6 (b)) would be used by itself as the final solution, but since it is very sensitive to changes in the velocity structure model, it is difficult to determine a unique solution. For this reason, both solutions are discussed.

Comparing the respective aftershock distributions for the 1978 and 2005 Miyagi-Oki earthquakes, it is seen that aftershocks of the 2005 earthquake occurred on the south-southeast side of the aftershock area of the 1978 Miyagi-Oki earthquake (Okada *et al*., 2005). Practically no aftershocks occurred southeast of the hypocenter, while the activity north of the hypocenter in this latest earthquake is lower than that in the 1978 Miyagi-Oki earthquake. Thus, aftershocks are mainly distributed west of the hypocenter; the characteristics of the aftershock distribution suggest that rupture propagated toward the west during the main shock.

As a result of analysis of the 2005 Miyagi-Oki earthquake, when either using the teleseismic waveforms alone or in tandem with the regional seismic waveforms, the slip distribution shows that after the principal rupture occurred in the vicinity of the hypocenter, rupture progressed toward the west. Based on the above discussion of the aftershock distribution, this can be said to be a natural result. Further, from Fig. 6, which compares the slip distributions for the 1978 Miyagi-Oki and 2005 earthquakes, it can be seen that the rupture area for the latest earthquake occurs in the same region as that for the 1978 Miyagi-Oki earthquake. Both the results obtained using the teleseismic waveforms and those using both the teleseismic waveforms and the regional seismic waveforms reveal large slip in the southeastern part of the 1978 rupture area, and expansion of the rupture toward the west. In the case of the joint inversion, the expansion toward the west is more pronounced. Thus, the rupture area of the 2005 earthquake is characterized by occurrence of the principal rupture in the southeastern part of the rupture area during the 1978 Miyagi-Oki earthquake and the subsequent westward progression of the rupture.

Seno *et al*. (1980) have estimated the rupture area of the 1978 Miyagi-Oki earthquake, and the result is shown in Figs. 6 (c) and (d). Comparison with the result by Yamanaka and Kikuchi (2004) shown in Figs. 6 (a) and (b) shows that both sets of results include 2 or 3 asperities or sub-faults in the northeastern and southwestern parts of the region. In both cases, these asperities are distributed north and west of the 2005 hypocenter. In both cases of Fig. 6, it seems that the large and small asperities indicated in the previous reports were not ruptured in the 2005 earthquake. However, it is believed that the 1978 rupture took place around the periphery of the 2005 earthquake. In particular, Seno *et al*. (1980) believed that there existed sub-faults with large slip amount in the vicinity of the 1978 hypocenter and in and around the 2005 earthquake rupture area. It is possible that the 2005 earthquake ruptured some of the same small asperities that had been ruptured by the 1978 earthquake. From research conducted thus far it appears that there is little possibility that rupture propagated northward from the hypocenter. Accordingly, within the rupture area of the 1978 Miyagi-Oki earthquake there must be asperities extending to the north that have yet to rupture.

6. Conclusions

The slip distribution for the 2005 Miyagi-Oki earthquake (August 16) was determined. The results indicate that the rupture process consisted of a main rupture in the vicinity of the hypocenter, followed by propagation of the rupture toward the west. This is compatible with the directivity seen in the teleseismic waveforms and the spread of the aftershock distribution.

Comparison with the slip distribution for the 1978 Miyagi-Oki earthquake revealed that the 2005 earthquake ruptured part of the rupture area of the 1978 Miyagi-Oki earthquake (particularly the southeastern part), but most of the asperities of the 1978 earthquake are not considered to have ruptured in the subsequent event. This suggests that the Miyagi-Oki earthquakes have been caused by several asperities rather than one large asperity. That is, several of these asperities ruptured simultaneously in the 1978 Miyagi-Oki Earthquake, but it is believed that in this latest earthquake only part of that region was ruptured. Thus, it is possible that a series of several Miyagi-Oki earthquakes will occur, as pointed out by Umino *et al*. (2005) for the 1933, 1936 and 1937 earthquakes. Consequently, in order to construct a model of Miyagi-Oki earthquakes, it is perhaps necessary to identify a group of asperities in which Miyagi-Oki earthquakes occur and then consider the possibility of successive rupture.

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References

Igarashi, T., T. Matsuzawa and A. Hasegawa, Repeating earthquakes and interplate aseismic slip in the northeastern Japan subduction zone, *J. Geophys. Res.*, **108**, 2002JB001920, 2003.

Hasegawa, A., Introduction to EPS special section for the M7.1 and M6.4 earthquakes in northeastern Japan, *Earth Planets Space*, **56**, i–iv, 2004.

Hasegawa, A., J. Nakajima, N. Umino, S. Miura, Deep structure of the northeastern Japan arc and its implications for crustal deformation and shallow seismic activity, *Tectonophysics*, **403**, 59–75, 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.Fjie and Y. Kaneda, Hypocenter distribution of the 2005 Miyagi-Oki earthquake and its aftershocks by OBS observation, *Presented at the 2005 annual meeting of the seismogical society of Japan*, 2005.

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

Nagai, R., M. Kikuchi and Y. Yamanaka, Comparative Study on the Source Processes of Recurrent Large Earthquakes in Sanriku-oki Region: the 1968 Tokachi-oki Earthquake and the 1994 Sanriku-oki Earthquake, *J. Seism. Soc. Japan*, **54**, 267–280, 2001.

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, *Geophys. Res. Lett.*, **32**, 2005GL024613, 2005.

Okada, T. and A. Hasegawa, The M7.1 May 26, 2003 off-shore Miyagi Prefecture Earthquake in northeast Japan: Source process and aftershock distribution of an intra-slab event, *Earth Planets Space*, **55** (No. 12), 731–739, 2003.

Okada, T., N. Umino, A. Hasegawa, Rupture process of the July 2003 northern Miyagi earthquake sequence,

NE Japan, estimated from double-difference hypocenter locations, *Earth Planets Space*, **55**(No. 12), 741–750, 2003.
Seno, T., K. Shimazaki, P. Somerville, K. Sudo and T. Eguchi, Rupture process of the Miyagi-Oki, JAPAN, earthquake of June 12, 1978, *Physics of the Earth and Planetary Interiors*, **23**, 39–61, 1980.
Suwa, Y., S. Miura, A. Hasegawa, T. Sato and K. Tachibana, Inter-plate coupling beneath the NE Japan arc inferred from 3 dimensional crustal deformation, *J. Seism. Soc. Japan*, **56**, 471–484, 2004.
Uchida, N., T. Matsuzawa, A. Hasegawa and T. Igarashi, Recurrence intervals of characteristic M4.8±0.1 earthquakes off Kamaishi, NE Japan – Comparison with creep rate estimated from small repeating earthquake data, *Earth Planet. Sci. Lett.*, **233**, 155–165, 2005.
Umino, N., T. Kono, T. Okada, J. Nakajima, T. Matsuzawa, N. Uchida, A. Hasegawa, Y. Tamura and G. Aoki, Relocation of past Miyagiken-oki earthquakes, *Presented at the 2005 annual meeting of the seismogical society of Japan*, 2005.
Yagi, Y., T. Mikumo (2004), J. Pacheco and G. Reyes, Source rupture process of the Tecoman, Colima, Mexico earthquake of January 22, 2003, determined by joint inversion of teleseismic body wave and near source data, *Bull. Seism. Soc. Am.*, **94**, 1795–1807, 2004.
Yamamoto, Y., R. Hino, M. Nishino, A. Kuwano, T. Yamada, T. Kanazawa, G. Aoki, T. Hashimoto, M. Abe, Seismic velocity structure and microseismicity in the off-Miyagi region, *Presented at the 2005 annual meeting of the seismogical society of Japan*, 2005.
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.

Table 1. Seismic velocity structure model

Depth(km)	V_P(km/s)	V_S(km/s)	Density ($\times 10^3$kg/m^3)	Q_P	Q_S
For far-field analysis					
0.0 - 1.0	4.90	2.83	2.3		
1.0 - 16.0	6.20	3.55	2.7		
16.0 - 31.0	6.70	3.87	3.1		
31.0 -	7.80	4.50	3.4		
For near-field analysis					
0.0 - 1.0	3.50	1.80	2.20	200	100
1.0 - 11.0	5.00	2.89	2.65	500	250
11.0 - 23.0	6.50	3.74	2.87	800	400
23.0 -	8.10	4.68	3.30	1200	600

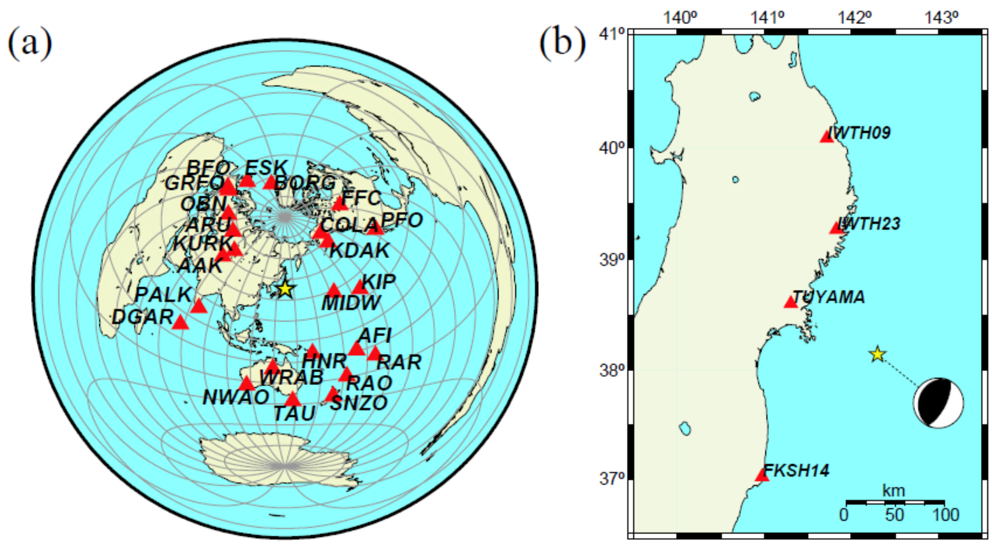

Fig. 1 : Distribution of observation stations (triangles) for which records were used in the analysis. The star shows the epicenter of the main shock. (a) Observation stations used to obtain the teleseismic body wave records. (b) Observation stations used to obtain the regional strong motion records.

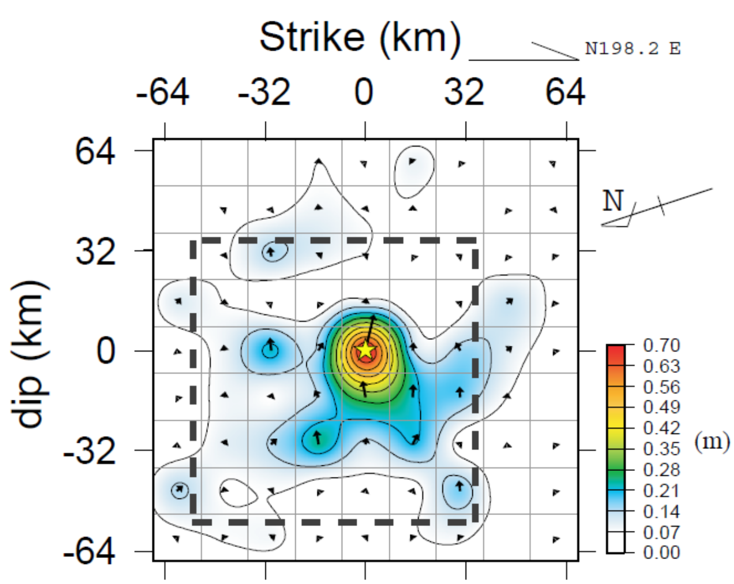

Fig. 2 : Final slip distribution. The star represents hypocenter of the mainshock, and slip vectors are shown with arrows. The dotted frame denotes the domain used in the joint inversion of the teleseismic waveforms and the regional seismic waveforms (Section 4.2; Fig. 5).

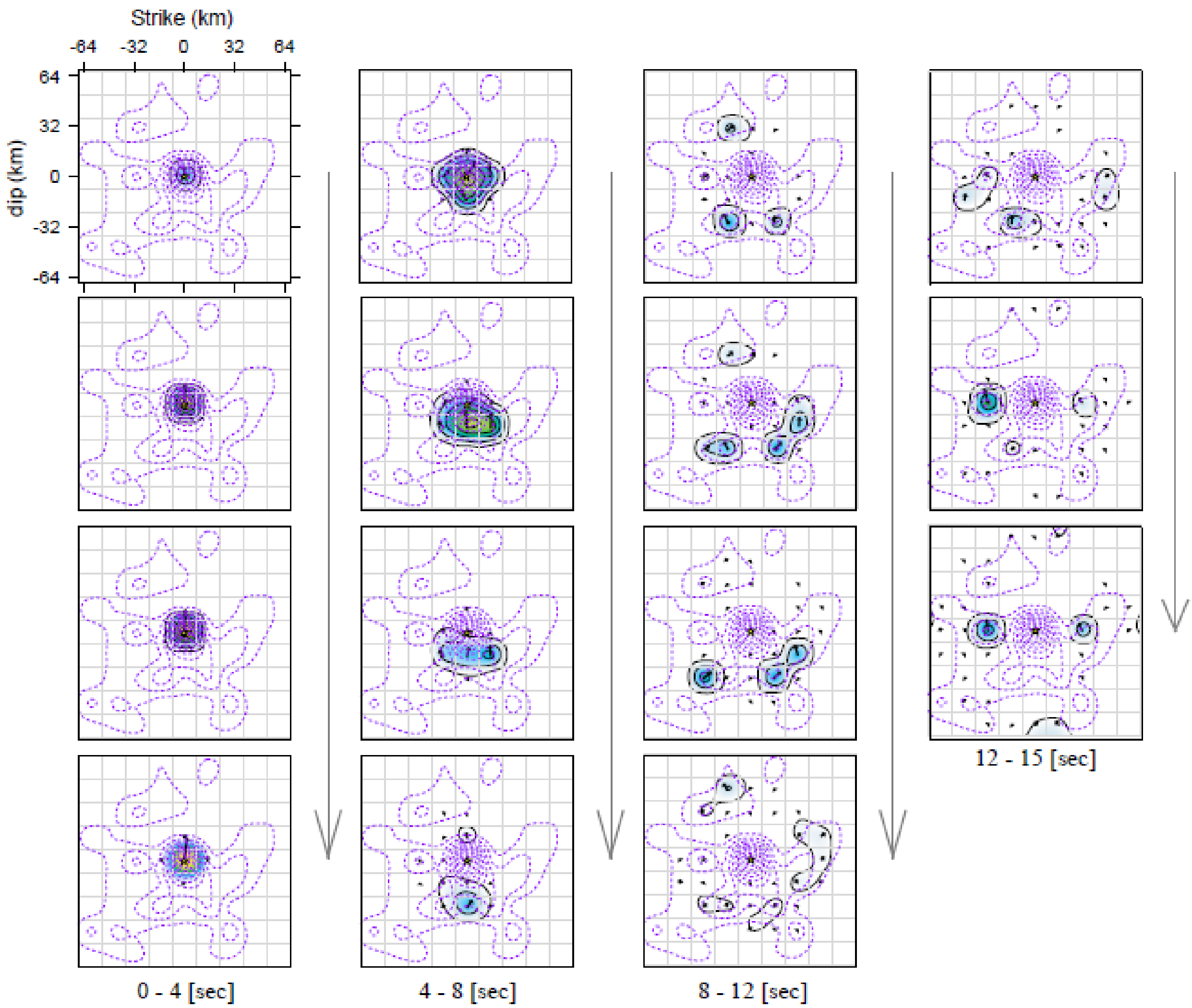

Fig. 3 : Evolution of rupture. Slip is shown at 1 s intervals (rupture starts from the upper left figure). Color scale is 1/3 of that in Fig. 2. Purple contours denote results for the final slip distribution.

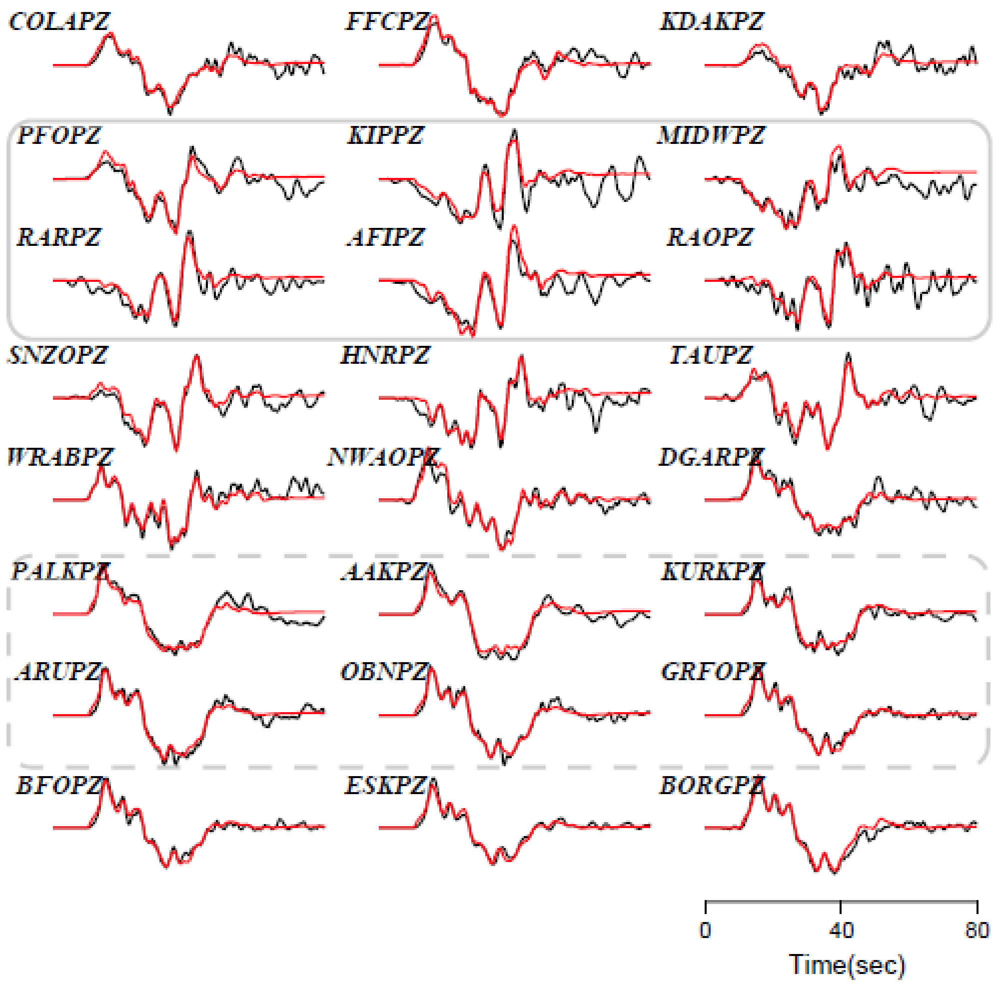

Fig. 4：Comparison of theoretical waveforms (red lines) with observed waveforms (black lines). Waveforms shown within the solid and wavy frames are the waveforms at the principal eastern observation stations and the principal western observation stations (discussed in Section 5).

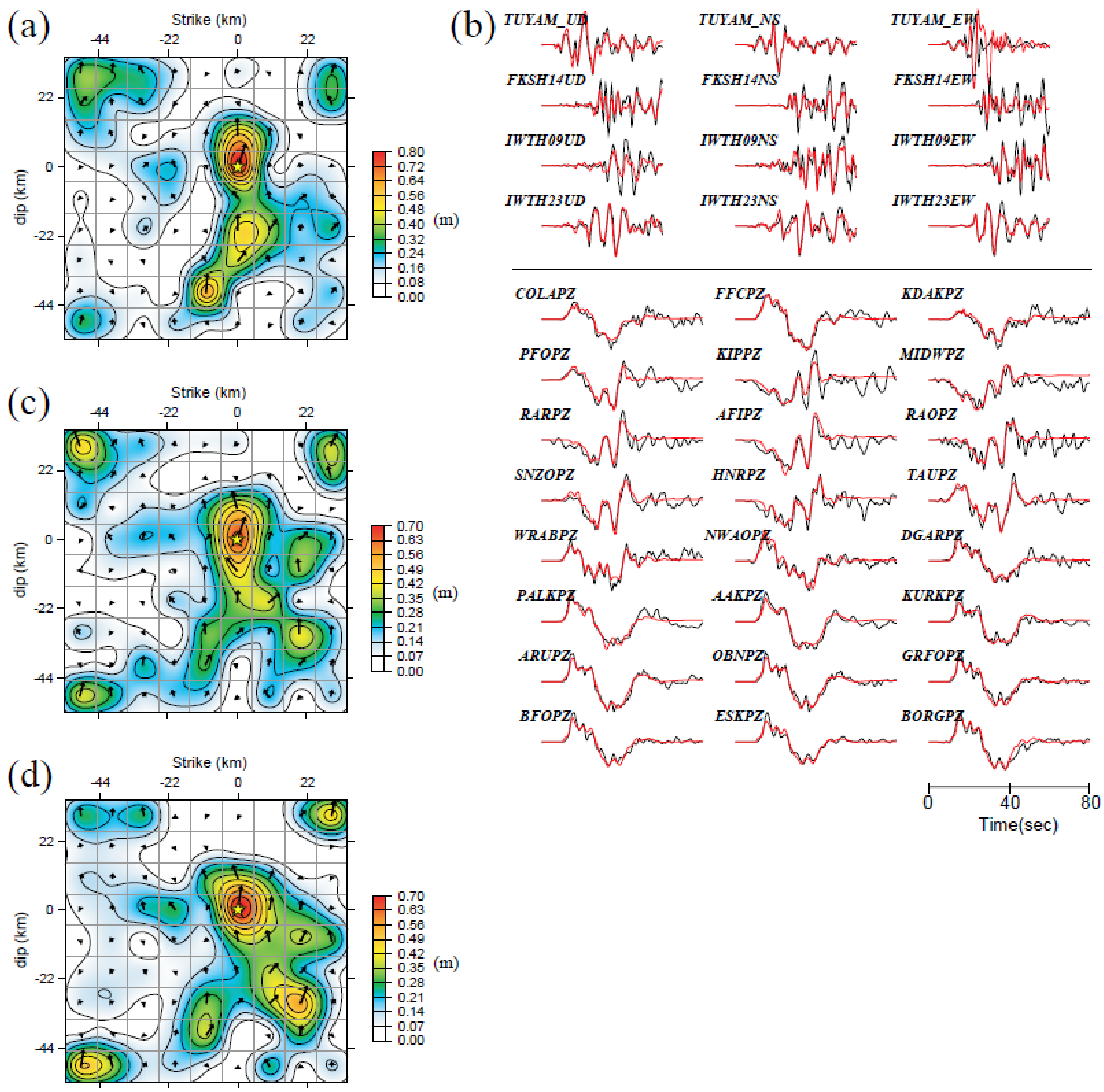

Fig. 5：Results of joint inversion analysis. (a) Final slip distribution (Moho at 23 km). (b) Comparison of theoretical waveforms and observed waveforms. Results for regional observation stations are shown above; results for teleseismic observation stations are shown below. (c,d) Final slip distributions for Moho depth of (c) 24 km and (d) 27 km.

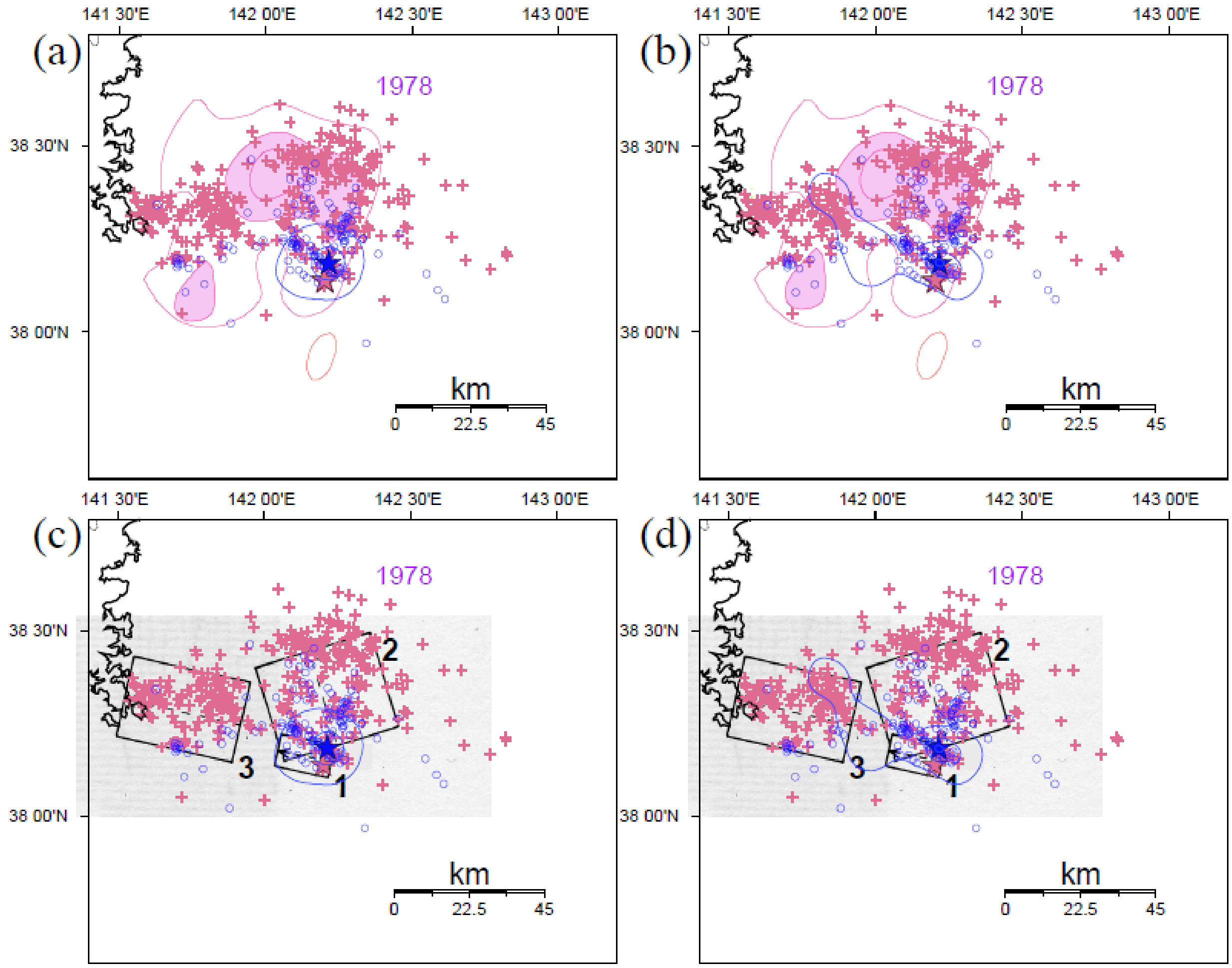

Fig. 6：Comparison of 2005 Miyagi-Oki earthquake (blue lines, slip distribution; blue circles, aftershock (2 days) epicenters) with the 1978 Miyagi-Oki Earthquake (red crosses, aftershock epicenters). The slip distribution contour interval is 0.3 m. Aftershock distribution was redetermined hypocenters by the DD method (Okada *et al*., 2005). (a,b) Comparison with the slip distribution (red lines) of Yamanake and Kikuchi (2004). (c,d) Comparison with the results of Seno *et al*. (1980); It is believed that large slip occurred in the areas denoted by rectangles. Teleseismic waveform inversion results are shown in (a) and (c), and joint inversion results are shown in (b) and (d).