# 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 more than 27 years have passed 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 it 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 a large slip occurred near the hypocenter and rupture extended to the westward deeper portion. Considering that the rupture area of the 2005 event partly overlapped with the southeastern part of that of the 1978 event, suggests this result the possibility that plural asperities exist which cause the sequence of Miyagi-Oki earthquakes and that the 2005 event ruptured one of such asperities, although the previous 1978 event ruptured all the asperities at one time.
**Key words:** Asperity, subduction zone, interplate earthquake, slip distribution.

## 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 6 lower in JMA scale was observed in Kawasaki, Miyagi Prefecture, where considerable damage was reported, including 91 people injured and one 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. 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 investigations 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 a large back slip is distributed in the source area of the Miyagi-Oki earthquake (Suwa *et al.*, 2004). Hasegawa (2004) suggested that the July 26 M6.4 earthquake was due to a 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.

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 |

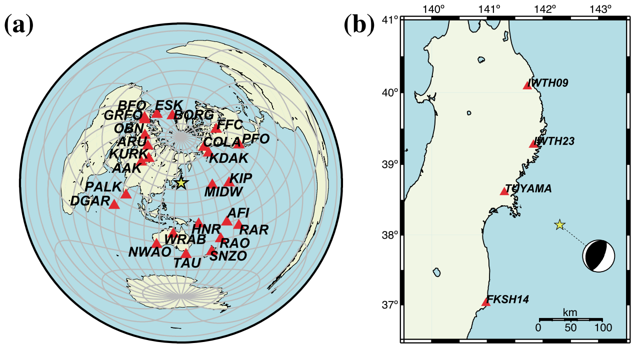


Fig. 1. Distribution of observation stations (triangles) for which records were used in the analysis. The star shows the epicenter of the main shock. (a) Observation stations used to obtain the teleseismic body wave records. (b) Observation stations used to obtain the regional strong motion records.

In this research, the analysis was carried out in two stages. First, the existence of a broad (135 × 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 × 90 km, and joint inversion of regional strong motion records and teleseismic body wave records was performed. The assumed fault plane was divided into 9 × 9 small faults in both of analyses.

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°, slip 81.9°. The slip-rate function on each subfault is composed of a series of eight triangle functions with a rise time of 1.0 s, and the maximum rupture velocity is set at 4.68 km/s, which is the same as $S$-wave velocity around the hypocenter (cf. Table 1). The assumed seismic velocity structure model is given in Table 1. This model is based on Ito *et al.* (2002), who obtained seismic structure of the northeastern Japan forearc by a seismic exploration using an Airgun-array. Ito *et al.*'s model shows that the depth of Moho varies around the focal area of the present earthquake. To test the robustness of the results on the assumed depth of Moho, we obtained three solutions using three models with different depths of Moho.

## 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 three basement strong motion observation stations of KiK-net borehole seismometers, 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, the station code of TUYAMA, were also used (Fig. 1(b)).

We selected those stations at which the observed waveforms can be explained to some extent by the assumed rough structure model used in this study. Consequently, four near stations were adopted with consistency of waveform fitting, which implies that the assumed model corresponds approximately to the real structure under those stations. Note that a revision of the velocity structure is necessary to explain more local waveforms in further studies.

Looking at the observed teleseismic waveforms in Fig. 4, especially (b), the rise in the waveform of $P$ wave differs between west and east: the rise is sharp and spiked at the western observation stations, and gradual and angled at the eastern observation stations. The overall appearance of the waveforms depends greatly on the direction of the observation stations. It can be therefore suggested that the difference in waveforms is due to the directivity.

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 using OBS data (Yamamoto *et al.*, 2005; Hino *et al.*, 2005).

## 4. Results

### 4.1 Results assuming a broad fault plane

The seismic moments obtained are $M_O = 8.8 \times 10^{19}$ Nm and $M_W = 7.2$. The estimated slip distribution is shown in Fig. 2(a). 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 the dip toward a greater depth (the west side). The process by which the rupture progresses in the direction of the 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 about 12 s after the onset. A comparison of the theoretical waveform and the observed waveform is shown in Fig. 4; the two agree reasonably well.

Of course there seems to be reactivated ruptures in the 13–15 s interval. The slip amount of this rupture was also

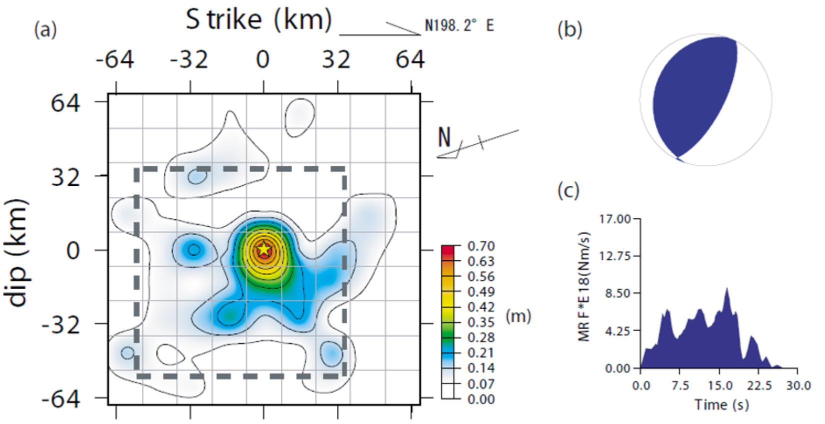


Fig. 2. (a) Final slip distribution (the interval of the contours is 0.07 m). The star represents the hypocenter of the mainshock, and slip vectors are shown with arrows. The dotted frame denotes the domain used in the joint inversion of the teleseismic waveforms and the regional seismic waveforms (Section 4.2; Fig. 5). (b) Focal mechanism. (c) Total moment-rate function.

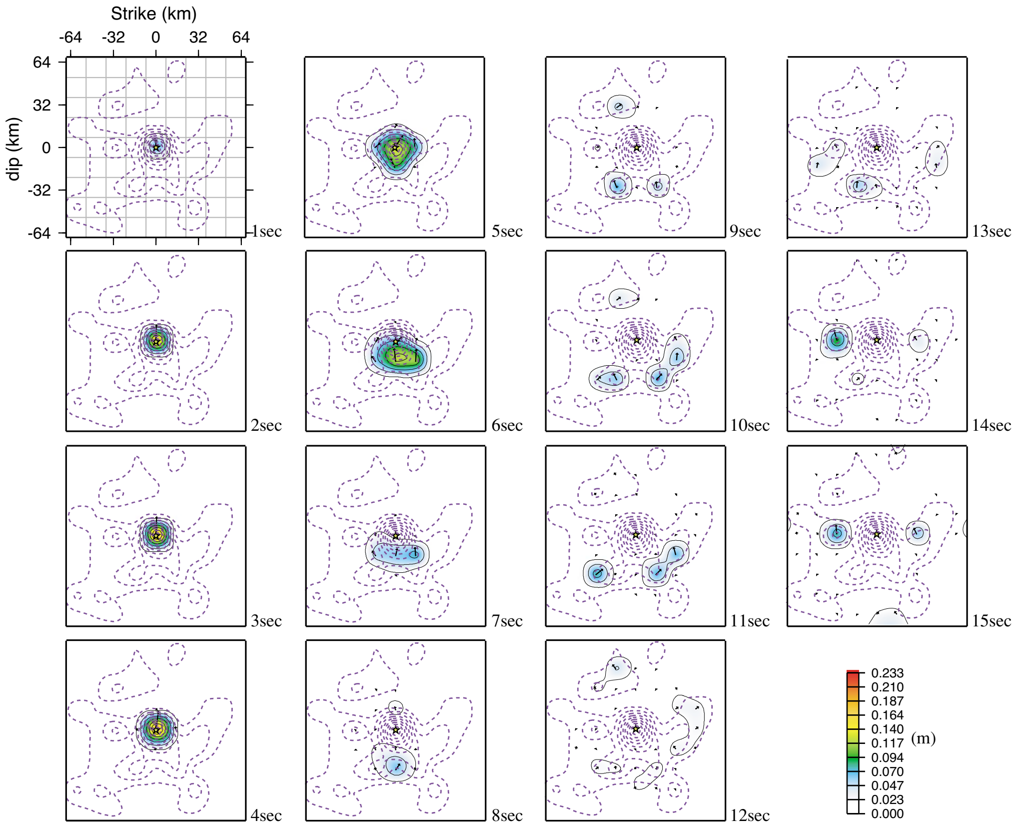


Fig. 3. Evolution of rupture. Slip is shown at 1-s intervals (rupture starts from the upper left figure). Color scale is one third of that in Fig. 2. Purple contours denote results for the final slip distribution.

relatively small, only 0.23 m. This may be not important in reproduction of the observed waveform and may be due to deviation of the actual seismic velocity structure from the assumed structure model in this study. Accordingly, this delayed rupture is not discussed further in the present paper.

The final slip distribution in Fig. 2(a) 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 a greater depth. This result is consistent with the directional dependence of the originally observed waveforms. Based on 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.

### 4.2 Results assuming a smaller fault surface

The obtained seismic moments are $M_O = 8.9 \times 10^{19}$ Nm and $M_W = 7.2$. The slip distribution and a comparison between the theoretical waveforms and the observed waveforms are shown in Fig. 5(a) and (b), respectively. Since this result is a result of joint inversion, the results for the four observation stations near strong motion are also shown. The maximum slip is about 0.82 m, which occurred near the

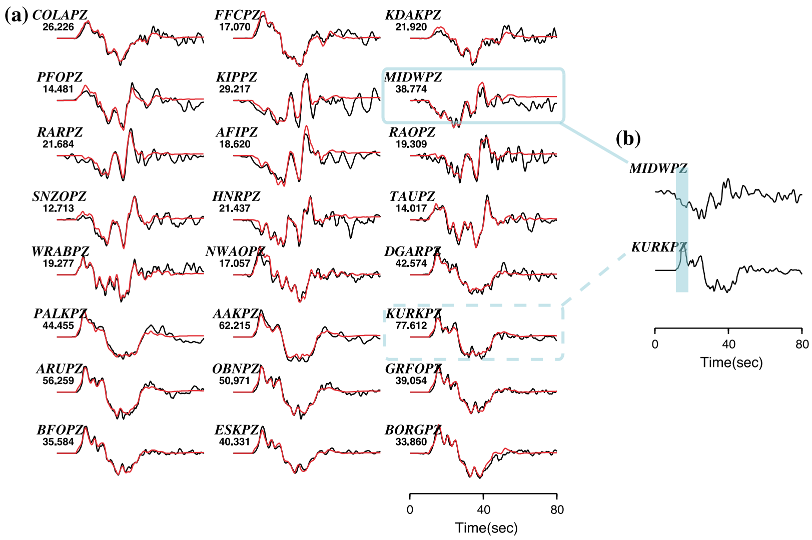


Fig. 4. (a) Comparison of theoretical waveforms (red lines) with observed waveforms (black lines). Waveforms shown within the solid and wavy frames are the waveforms at the principal eastern observation station and the principal western observation station, respectively (discussed in Section 3). The maximum amplitude of each station is indicated below its code (microns). (b) The waveforms at the principal eastern observation station (MIDWPZ) and the principal western observation station (KURKPZ). The aqua ranges indicate approximate lengths of the rise of the waveform.

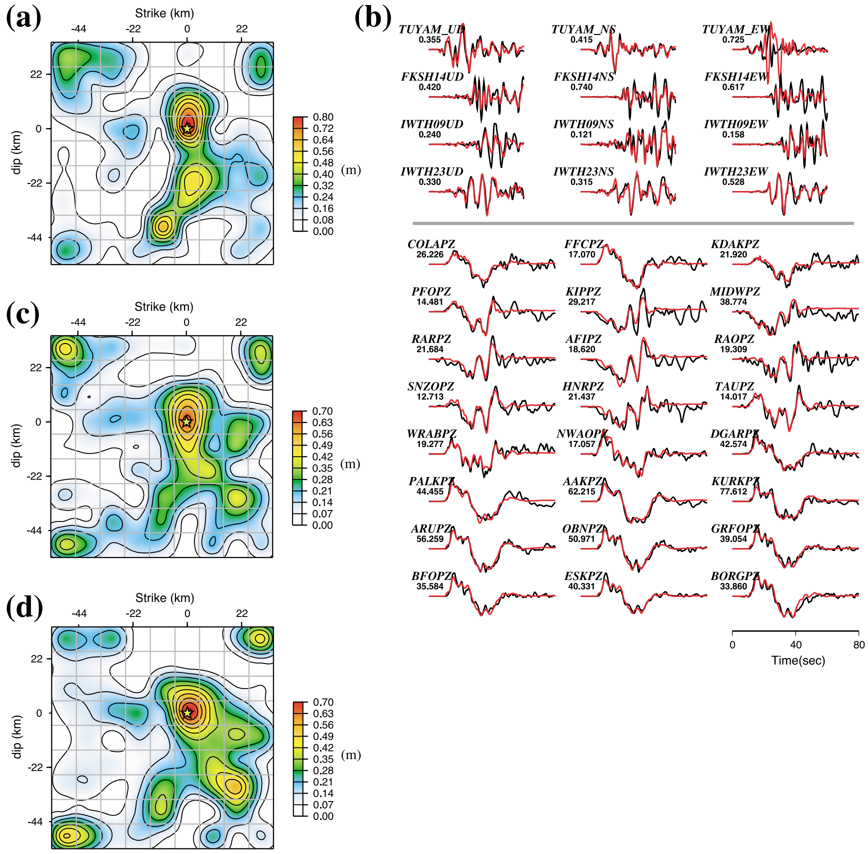


Fig. 5. Results of joint inversion analysis. (a) Final slip distribution (Moho at 23 km). (b) Comparison of theoretical waveforms and observed waveforms. Results for regional observation stations are shown above; results for teleseismic observation stations are shown below. The maximum amplitude of each station is indicated below its code (regional observation station: centimeters, teleseismic observation station: microns). (c,d) Final slip distributions for Moho depth of (c) 24 km and (d) 27 km.

point where the main shock rupture initiated.

The slip distributions when the depth of Moho in the velocity structure model is varied are shown in Fig. 5(c) and (d). The maximum slips shown in (c) and (d), which occurred near the point where the main shock rupture initiated, are about 0.66 m and 0.71 m, respectively. In all of the slip distributions, relatively large slip occurs at the corners of the assumed fault plane. This may be related to the assumed velocity structure model, as in the case shown in Section 4.1.

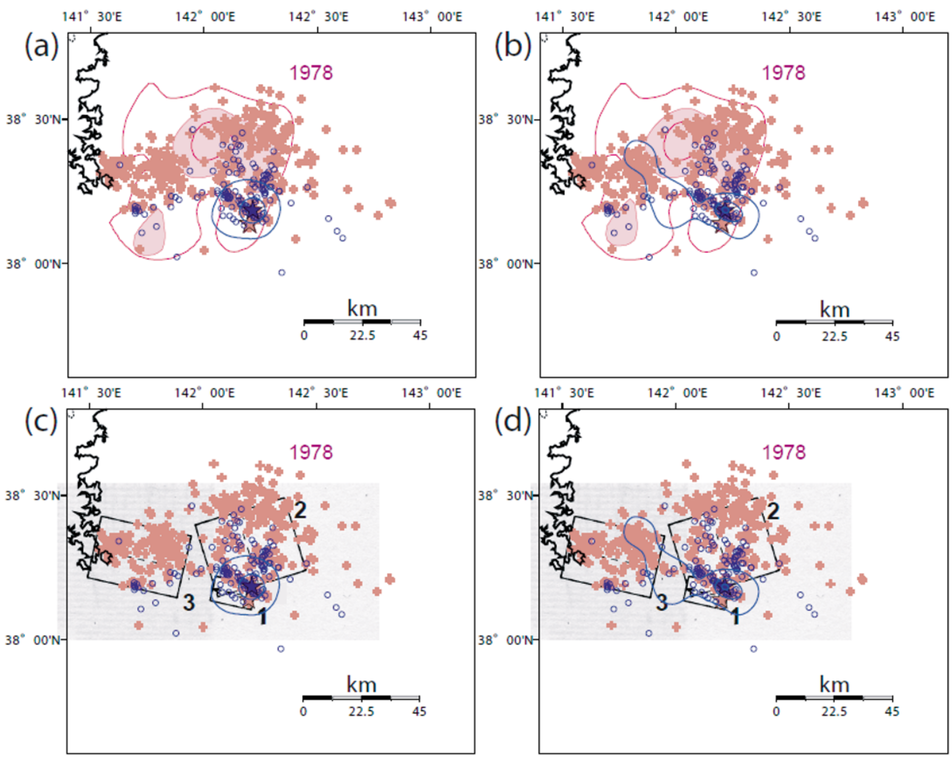


Fig. 6. Comparison of 2005 Miyagi-Oki earthquake (blue lines, slip distribution; blue circles, aftershock (2 days) epicenters) with the 1978 Miyagi-Oki earthquake (red crosses, aftershock (2 days) epicenters). The slip distribution contour interval is 0.3 m. Aftershock distribution was redetermined hypocenters by the double-difference method (Okada *et al.*, 2005). (a, b) Comparison with the slip distribution (red lines) of Yamanaka and Kikuchi (2004). (c, d) Comparison with the results of Seno *et al.* (1980); It is believed that a 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).

The slip distribution indicates that after the large slip in the vicinity of the hypocenter, rupture propagated in the direction of the dip to a greater depth (toward the west). A comparison of Fig. 5(c) and (d) reveals that when the assumed depth of Moho is changed, the details of the slip distribution also change. Thus, the obtained slip distribution appears to be affected by variations in the assumed velocity structure. However, these 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 an analysis using only the teleseismic waveforms, although the latter feature is depicted more clearly.

Note that the east-west component at the Tsuyama (TUYAM_EW) station was less-weighted because when we apply the same weight to this component as other components and other stations, the waveform at the western far stations could not be explained well. This is probably caused by a difference between the structure in the vicinity of the Tsuyama observation station and/or along the path and that used in the present analysis.

## 5. Discussion—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. Figure 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 by 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.

Our comparison of the respective aftershock distributions for the 1978 and 2005 Miyagi-Oki earthquakes reveals 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). The activity north of the hypocenter in this latest earthquake is lower than that in the 1978 Miyagi-Oki earthquake, while aftershocks are mainly distributed west of the hypocenter. This comparison of the aftershock distributions between the 1978 and 2005 Miyagi-Oki earthquakes also suggests that the rupture propagated toward the west and did not propagate toward the north from the hypocenter during the main shock.

Analysis of the 2005 Miyagi-Oki earthquake, using either the teleseismic waveforms alone or in tandem with the regional seismic waveforms, in terms of 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 overlaps with the southeastern part of the 1978 Miyagi-Oki earthquake. Therefore, the rupture area of the 2005 earthquake is characterized by the 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 Fig. 6(c) and (d). Comparison with the result by Yamanaka and Kikuchi (2004), shown in Fig. 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 northern and small southwestern asperities indicated in the previous reports were not ruptured in the 2005 earthquake. Furthermore, Seno *et al*. (1980) suggested that there sub-faults with large slip amount exist in the vicinity of the 1978 hypocenter, and this study suggested that the 2005 earthquake ruptured around the hypocenter of the 1978 earthquake. Therefore, one of the possible interpretations is that there are some asperities in the Miyagi-Oki region, and the 2005 earthquake ruptured parts of the asperity, near the hypocenter at least, that had been ruptured by the 1978 earthquake.

## 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, it is suggested that several of these asperities ruptured simultaneously in the 1978 Miyagi-Oki Earthquake, while one of the asperities ruptured in this latest earthquake. 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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