SOURCE PROCESSES OF LARGE EARTHQUAKES PRECEDING THE 2011 TOHOKU-OKI EARTHQUAKE, DETERMINED BY JOINT INVERSION OF TELESEISMIC AND NEAR-SOURCE DATA

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ABSTRACT

A sequence of M7-class interplate earthquakes (M6.7-7.3) occurred from 2003 to 2011 before the occurrence of the M9 2011 Tohoku-oki earthquake. To investigate the relationship between these previous events and the giant earthquake, we determined the source processes of these events by joint inversion method. We performed the inversions by using both near source and teleseismic body-wave data. To perform a stable inversion, we applied smoothing constraints, and determined their optimal relative weights on the observed data using an optimized Akaike's Bayesian Information Criterion (ABIC). The results show that the rupture areas of these M7-class events were nearly covered by the rupture area of the 2011 Tohoku-oki earthquake determined by Yagi and Fukahata (2011). The epicenter or the initial rupture of the giant earthquake was located in the un-rupture region surrounded by the rupture areas of the 2003 Fukushima-ken-oki earthquake, the 2005 Miyagi-ken-oki earthquake and the 2011 Sanriku-oki earthquake. At the first stage of the source process, the rupture propagated southeast and broke the asperity where the maximum slip occurred, and the asperity was also located in the un-rupture region which was close to the source regions of the 2003 Fukushima-ken-oki earthquake and the 2011 Sanriku-oki earthquake.

Keywords: Teleseismic Wave, Strong Motion, Source Rupture Process, Joint Inversion

1. INTRODUCTION

On March 11, 2011, a giant earthquake with magnitude 9.0 occurred off the Pacific coast of northern Honshu. It resulted from thrust faulting on or near the plate boundary between the Pacific and North America Plates. The strong ground shaking and large tsunami generated by this giant earthquake caused significant casualties and damage. Before this M9 giant event, several M7-class earthquakes occurred near the source region from 2003 to 2011: (1) October 31, 2003, Fukushima-ken-oki earthquake (M_j 6.8, JMA magnitude); (2) August 16, 2005, Miyagi-ken-oki earthquake (M_j 7.2); (3) May 7, 2008, Ibaraki-ken-oki earthquake (M_j 7.0); (4) July 19, 2008, Fukushima-ken-oki earthquake (M_j 6.9); (5) March 14, 2010, Fukushima-ken-oki earthquake (M_j 6.7) and (6) March 9, 2011, Sanriku-oki earthquake (M_j 7.3). The JMA results show that these six interplate earthquakes have similar focal mechanism as the 2011 Tohoku-oki earthquake. They all occurred along the Japan Trench because of the low-angle thrust faulting on the subduction zone. These events can be considered as the long-term pre-seismic signals of the Tohoku-oki earthquake. To gain understandings of the preparation process of giant earthquake, it is necessary to investigate the source processes of these M7-class events.

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2. DATA

In this study, We obtained teleseismic body wave data recorded by IRIS-DMC. 177 components of 61 teleseismic stations were selected. We chose the stations of epicentral distance ranges from 30° to 90°. We also used 96 components of near-source data obtained from 23 strong motion seismograph stations of the K-NET operated by NIED. The teleseismic body waveforms were converted into displacement with sampling time 0.25 sec and the near-source data were integrated into velocity with sampling time 0.25 sec.

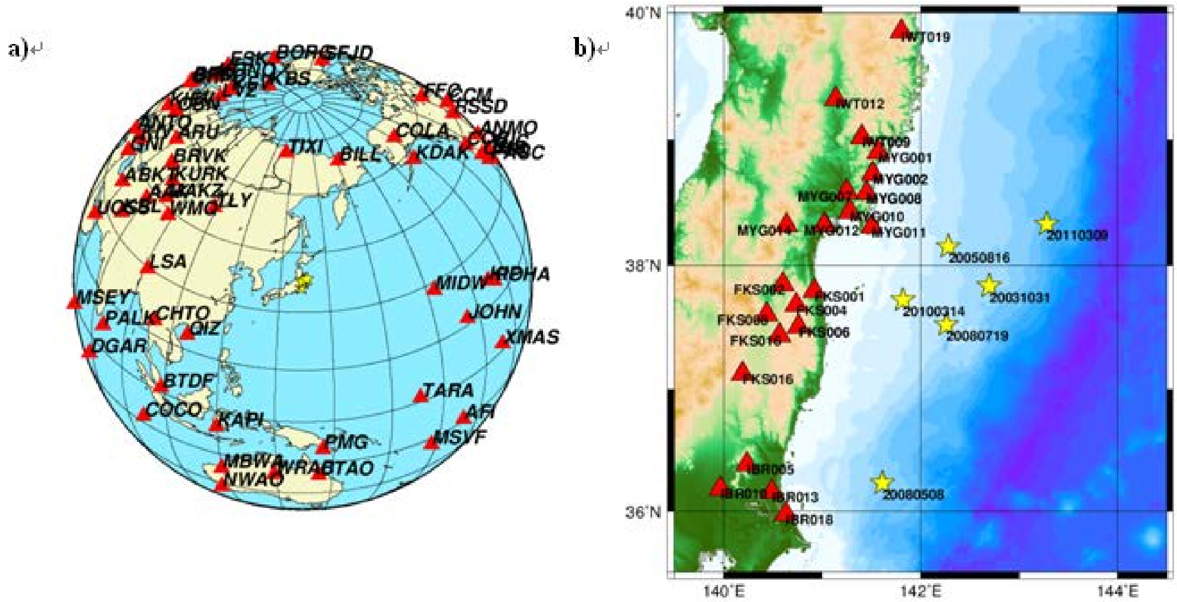

Figure 1. The distribution map of teleseismic stations: the stars represent the epicenters of the events; red triangles indicate stations. a) teleseismic network, b) strong motion network.

3. THEORY AND METHODOLOGY

To construct the source model and obtain the source processes of the six interplate earthquakes, we used a numerical method developed by Yagi *et al*. (2004), whose basic theory follows the standard waveform inversion scheme (Hartzell and Heaton, 1983). The rupture process is represented as a spatiotemporal slip distribution on a fault plane. We divided the fault plane into multiple subfaults. Then we described the slip-rate function on each subfault by a series of triangle functions with rise time. We calculated the Green's function for teleseismic body wave data by the method of Kikuchi and Kanamori (1991). For near-source strong ground motion we used the discrete wave number method developed by Kohketsu (1985). We applied the velocity structure based on a simple-layered oceanic model referred to the Jeffreys-Bullen model (Jeffreys, 1970). To simplify the calculation and obtain more stable results, we applied smoothing constraints to the slip distribution with respect to time and space to obtain more stable results. With the constraints, we can determine the model parameters that minimize the residual sum of squares. To get the values of variances we applied the minimum Akaike's Bayesian information criterion (ABIC) (Akaike, 1980). The optimal ABIC formulation of two types for partially-dependent prior information was developed by Fukahata *et al*. (2003). We applied a grid-search method to obtain optimal values of variances which minimize ABIC, and employed the non-negative least squares (NNLS) algorithm of Lawson and Hanson (1974) to solve the least squares problem with a positivity constraint on the model parameters.

4. RESULTS AND DISCUSSION

Assuming the faulting occurs on the single fault plane and that the slip angle remains unchanged during the rupture, we adopted the focal mechanism and the epicenter determined by JMA. We constructed our fault model with a length along the strike and a width along dip to obtain a rough estimate of the rupture area. Then we set the number and size of the subfaults on the fault plane. Since the focal depth is not adequately constrained by the local seismological network, we varied the value in the inversion procedure with the focal mechanism and epicenter fixed, and found its minimum variance.

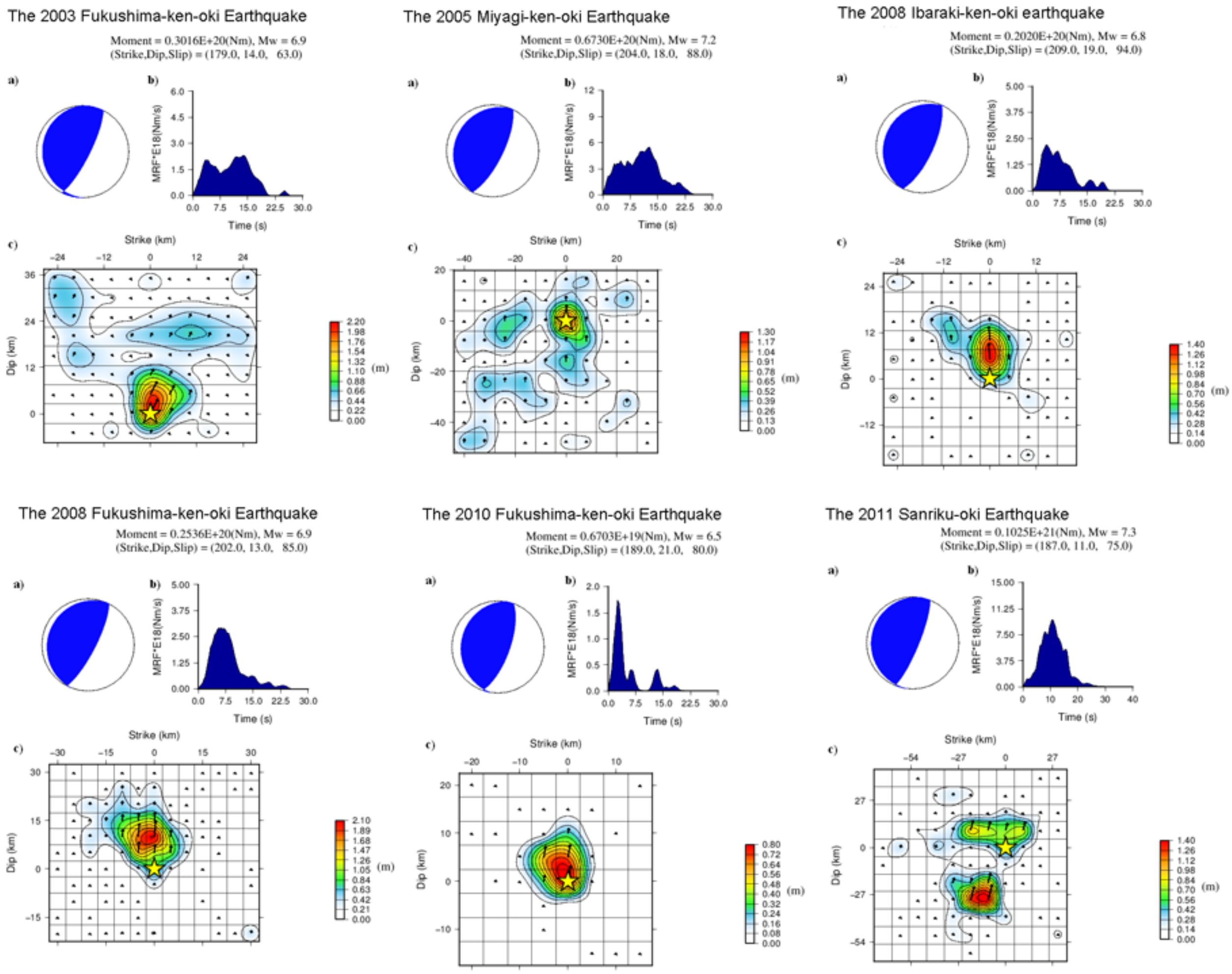

Figure 2. Joint inversion results of M7-class earthquakes.
a) Focal mechanism, b) source time function, c) slip distribution

Figure 2 gives the inversion results of these M7-class events before Tohoku-oki Earthquake. The source durations, the focal mechanisms of these earthquakes and the final dislocation on the fault plane are shown here. The source time functions indicate the total seismic moments of these events. Our results seem almost in agreement with the CMT moments determined by JMA. The comparison of the observed data and the synthetic waveform is shown in Figure 3: The overall fit is quite good.

The relationship between these M7-class events and the giant earthquake was discussed by combining the results obtained from the preceding analysis. Figure 4 superimposes these slip distributions of the M7-class events with that of the 2011 Tohoku-oki earthquake (Yagi and Fukahata, 2011). The colored contour interval of each coseismic slip is 10 cm and the Tohoku-oki earthquake's black contour interval is 5 m. The yellow stars represent the epicenters of the M7-class events; the red star indicates the epicenter of the giant one. The green broken lines indicate isodepth contours of the plate interface with 10-km intervals (Nakajima and Hasegawa, 2006) and the black one represents the Japan Trench.

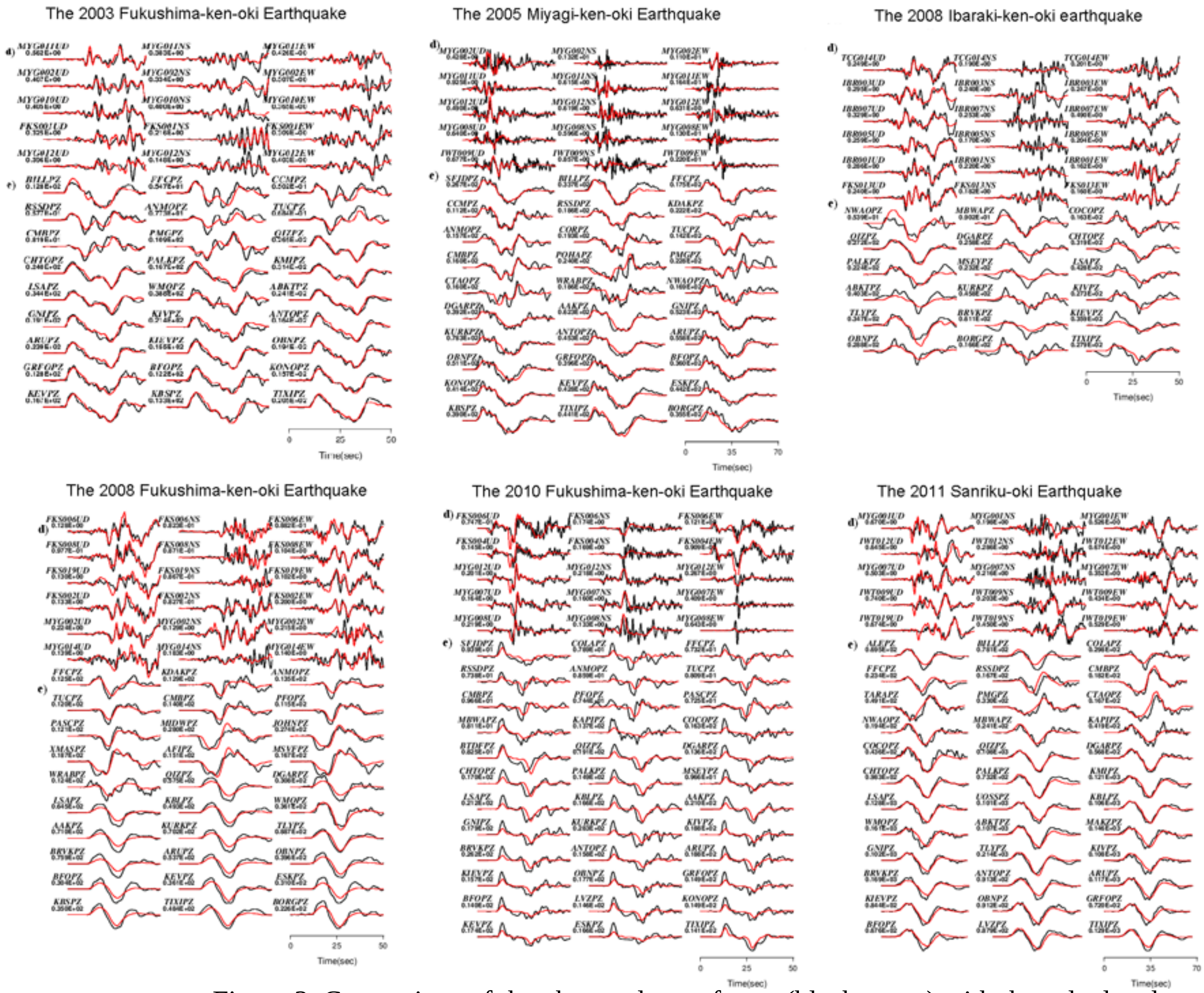

Figure 3. Comparison of the observed waveforms (black curve) with the calculated waveforms (red curve)

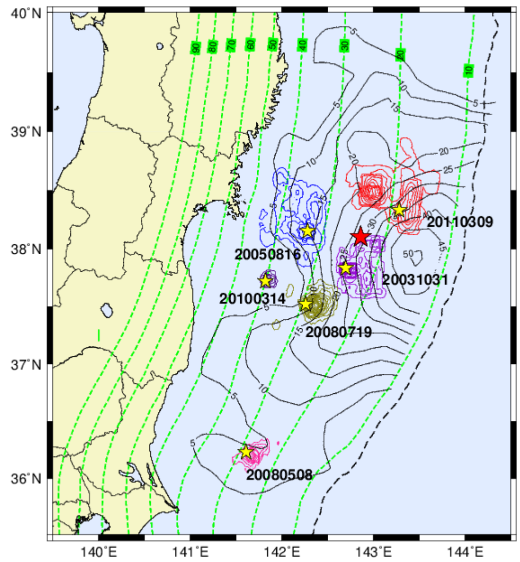

Figure 4. Coseismic slip distribution of six events and the Tohoku-oki earthquake

In this figure the rupture areas of these M7-class events were nearly covered by that of the Tohoku-oki earthquake. The epicenter of the giant earthquake was located at the gap of the rupture areas of these events. The rupture propagated southeast during the first 20 s, broke the asperity to the northeast of the source region of the 2003 Fukushima-ken-oki earthquake and the southeast of that of the 2011 Sanriku-oki earthquake. The rupture was greatly accelerated around this area where the maximum slip finally got over 50 m. At the same time, the rupture started at 20 s in the source region of the 2005 Miyagi-ken-oki earthquake. After 40 s, the rupture extended widely towards both north and south, as shown in Figure 5. In this figure, which compares the slip distributions for the six M7-class events and initiation process of the 2011 Tohoku-oki earthquake, it can be seen that the Tohoku-oki earthquake initiated the region surrounded by the rupture areas of the 2003

Fukushima-ken-oki earthquake, the 2005 Miyagi-ken-oki earthquake and the 2011 Sanriku-oki earthquake. Therefore, the initial rupture area of the Tohoku-oki earthquake is characterized by the occurrence in the un-rupture region surrounded by the large earthquakes preceding it. At this first stage of the source process, the rupture broke the asperity or sub-faults where the maximum slip occurred.

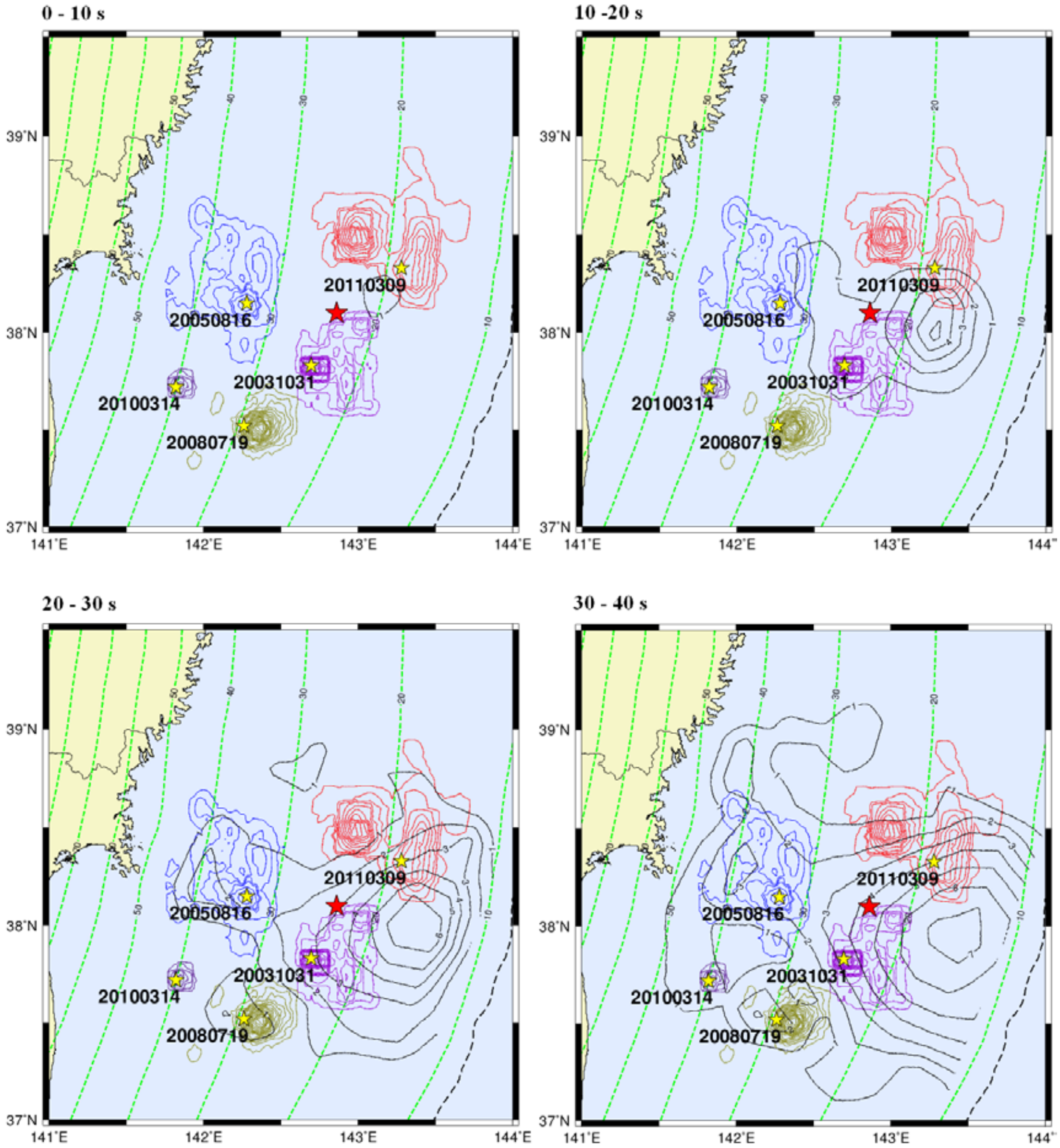

Figure 5. Snapshots of the rupture propagation of the 2011 Tohoku-oki earthquake at 10-s intervals from 0 – 40 s (Yagi and Fukahata, 2011)

5. CONCLUSIONS

Applying the joint inversion method developed by Yagi *et al.* (2004) that uses the near source strong motion data and teleseismic body wave data, we determined detailed source fault models and spatiotemporal slip distributions of a sequence of M7-class interplate earthquakes from 2003 to 2011 along the Japan Trench preceding the 2011 Tohoku-oki earthquake.

The results indicate that the slip distributions of the 2008 Ibaraki-ken-oki earthquake, the 2008 Fukushima-ken-oki earthquake and the 2010 Fukushima-ken-oki earthquake are relatively similar: The source process consisted of a main rupture in the vicinity of the hypocenter, followed by propagation of the rupture toward the east, and extended area is limited. The inversion results of the 2003 Fukushima-ken-oki earthquake, the 2005 Miyagi-ken-oki earthquake and the 2011 Sanriku-oki earthquake show different characteristics of source process. The source processes of these events are characterized by the large rupture.

Comparison with the slip distribution for the M7-class events revealed that the rupture area of the 2011 Tohoku-oki earthquake determined by Yagi and Fukahata (2011) covered most of those of the M7-class earthquakes. The epicenter or the initial rupture of the giant earthquake was located in the un-rupture region surrounded by the rupture areas of the 2003 Fukushima-ken-oki earthquake, the 2005 Miyagi-ken-oki earthquake and the 2011 Sanriku-oki earthquake. At the first stage of the source process, the rupture propagated southeast and broke the asperity where the maximum slip occurred, and the asperity also was located in the un-rupture region which was close to the source regions of the 2003 Fukushima-ken-oki earthquake and the 2011 Sanriku-oki earthquake.

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