Change of the source mechanism of the main shock of the 2004 off the Kii peninsula earthquakes inferred from long period body wave data

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Waveform inversion of long period body wave data was performed to determine the temporal distribution of moment release of the main shock of the 2004 off the Kii peninsula earthquakes. Our result suggests that the source mechanism varied during the rupture, with the first 20 sec dominated by the strike slip component, while a thrust mechanism was predominant between 30–40 sec. The employed dataset has enough resolving power to detect temporal change on such a time scale, and thus our results suggest that this earthquake is a compound event consisting of the two different source mechanisms.

Key words: Moment tensor, temporal distribution, long period body wave.

1. Introduction

Recently, we developed a new technique to determine the temporal distribution of moment release of large earthquakes by inversion of long period body wave data (Hara, 2004). In the present study, we applied this technique to the analysis of the main shock of the 2004 off the Kii peninsula earthquakes (origin time: September 5, 2004 14:57:18 UTC; location: 33.15°N 137.04°E; depth: 10 km; Mw: 7.4 after USGS). A slightly modified version of the original technique was used as described in the next section.

2. Analysis

Long period channel data from the IRIS DMC was used in this analysis. In this study, we used the seismograms from the beginnings of the records to the arrival of surface waves, calculated the Fourier spectra, corrected for the instrumental response, and employed the spectra in the frequency band between 0.01–0.02 Hz.

Our analysis consisted of two steps. In the first step, a CMT solution was determined to find an optimum centroid location. In the second step, the centroid location was fixed and an inversion was performed to determine the temporal distribution of moment release.

A grid search approach was adopted for the first step to avoid the effect of choice of initial values in the iterative linearized inversion which is usually used in CMT inversions (e.g., Dziewonski and Woodhouse, 1983). The study area was covered with a 5×5 horizontal grid with 25 km spacing between grid points (Fig. 1(a)). The center grid is placed at the epicenter reported by the USGS. There were 3 grids vertically at depths of 10, 20 and 30 km. Five temporal grids were set with an interval between the adjacent grids of 10 seconds. We calculate the Green's function for each moment tensor component for each pair of the space and time grids using the Direct Solution Method (Cummins *et al.*, 1994; Takeuchi *et al.*, 1996). We used PREM (Dziewonski and Anderson, 1981) as an earth model in the present study. An inversion was performed for a moment tensor for each pair of the space and time grids under the condition that the trace of the moment tensor was zero.

Figure 1(b) shows the results obtained for the space grids at a depth of 20 km at the time grid 30 seconds after the origin time. The solid circle in Fig. 1(b) represents the space grid for which the largest variance reduction was obtained among all of the pairs of the space and time grids, and represents the centroid location. The centroid of the Harvard CMT solution is located at 33.08°N, 137.31°E, which is east of the epicenter determined by the USGS, while our analysis located the centroid west of the epicenter. It is difficult to have tight constraint on the absolute centroid location in our analysis, since we did not consider the effect of three-dimensional earth structure for seismic wave propagation. However, considering aftershock distribution (Fig. 1(a)) and rupture model (e.g., http://iisee.kenken.go.jp/staff/yagi/eq/Japan20040905/Japan20040905_1-j.html), it seems that our estimate is reasonable.

In the second step, we performed an inversion to determine temporal distribution of moment release following Hara (2004). Hara (2004) assumed that synthetic seismograms were expressed by a summation of the product of the moment tensor component at each time grid and its corresponding Green's function computed for the fixed centroid. Then, he performed a waveform inversion to determine the moment tensor at each time grid simultaneously. This inverse problem is linear and the temporal change of the source mechanisms is allowed.

As a fixed centroid location, we chose that determined in the first step. Hara (2004) assumed the moment rate function at each time grid was given by the delta function. We modified this assumption, and adopted triangle functions to

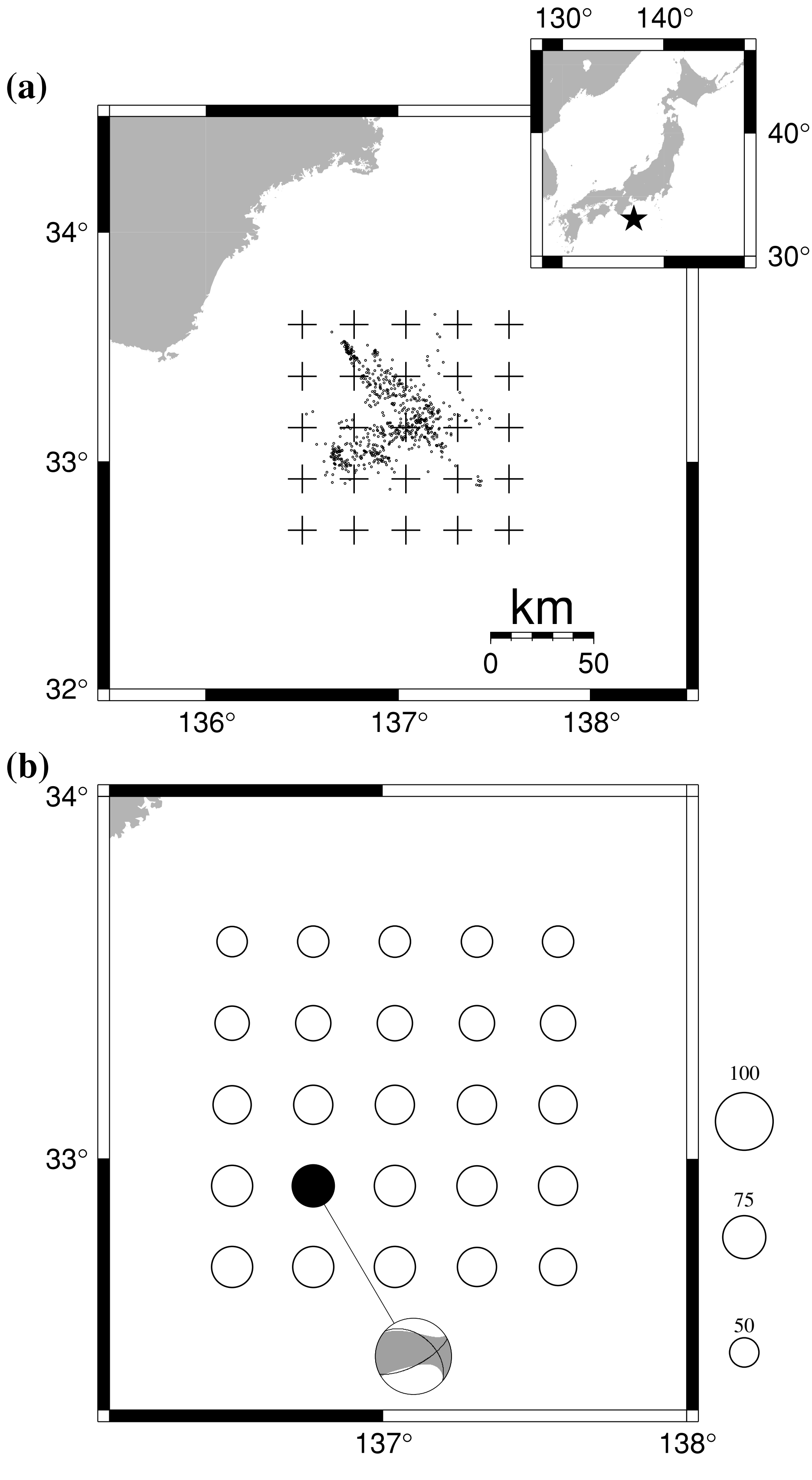
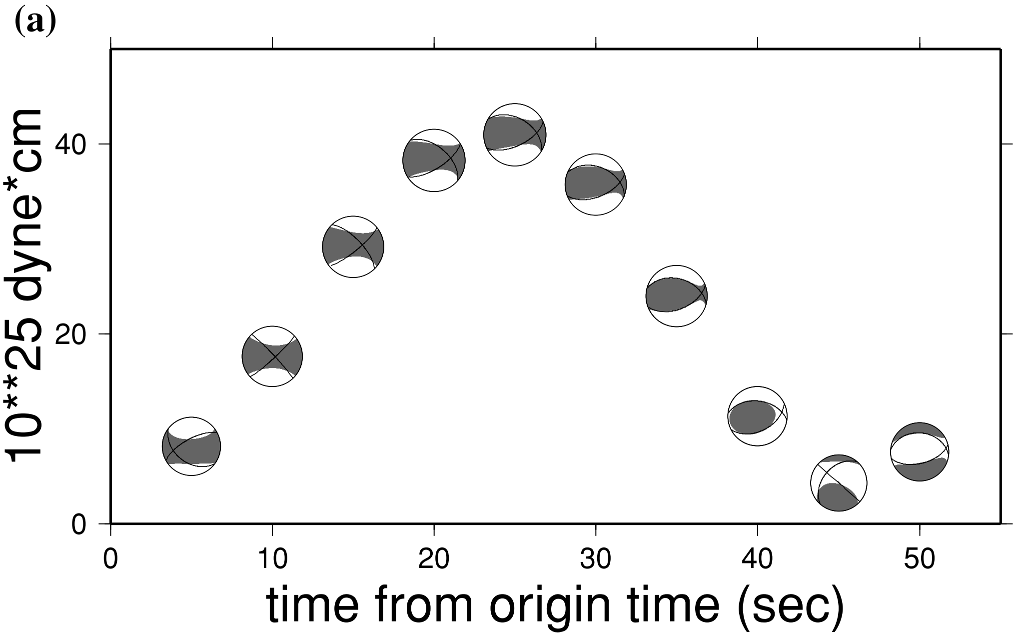


Fig. 1. (a) The pluses denote the horizontal grid. The dots denote aftershock epicenters determined by Japan Meteorological Agency that occurred since the foreshock (origin time: September 5 10:07:07 UTC after USGS) till September 7. The star in the upper right panel is the epicenter determined by the USGS. (b) The variance reduction obtained by inversion using the Green's functions computed for each grid at a depth of 20 km for the time grid 30 seconds after the origin time. The diameters of circles are proportional to the variance reduction (the scale is shown in the right-hand side). The solid circle represents the space grid for which the largest variance reduction was obtained among all of the pairs of the space and time grids (the source mechanism is also plotted).



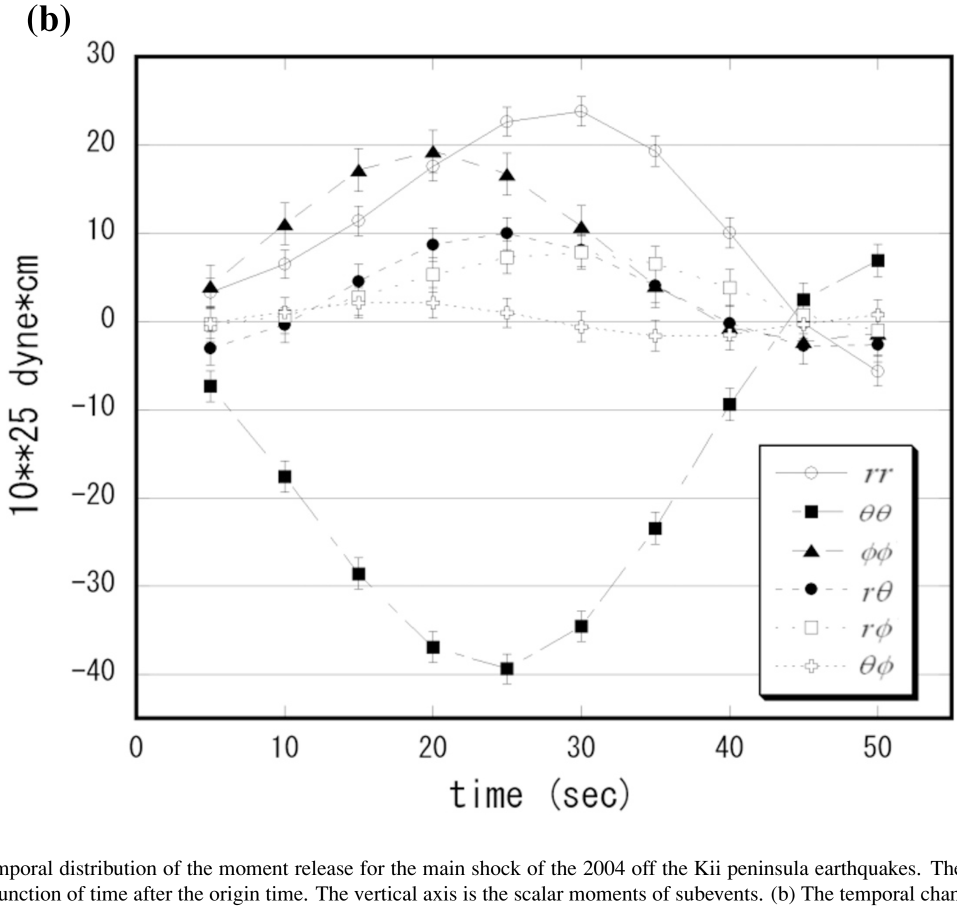


Fig. 2. (a) The temporal distribution of the moment release for the main shock of the 2004 off the Kii peninsula earthquakes. The focal mechanisms are shown as a function of time after the origin time. The vertical axis is the scalar moments of subevents. (b) The temporal change of each moment tensor component. The error bars represent the two times standard deviation.

account for the finite rise time. The total rupture duration was set to 50 seconds, and put 10 time grids at every 5 sec. The duration of the unit triangle function is 10 sec, and its area is normalized. The height of the triangle function for each moment tensor component at each time grid is the unknown in the present inverse problem. The total number of unknowns is 50, since we assumed that the trace of the moment tensor was zero. Following Hara (2004), we employed a smoothness constraint. We varied the damping factor, and found a solution that was consistent with the CMT solution, which was the solution obtained in the first step in this case. The details of this procedure are presented by Hara (2004).

Figure 2 shows the result. The total variance reduction is 81.2 per cent. Figure 3 shows examples of the observed and synthetic spectra for some stations. For the first 20 sec during the rupture, the strike slip component was dominant

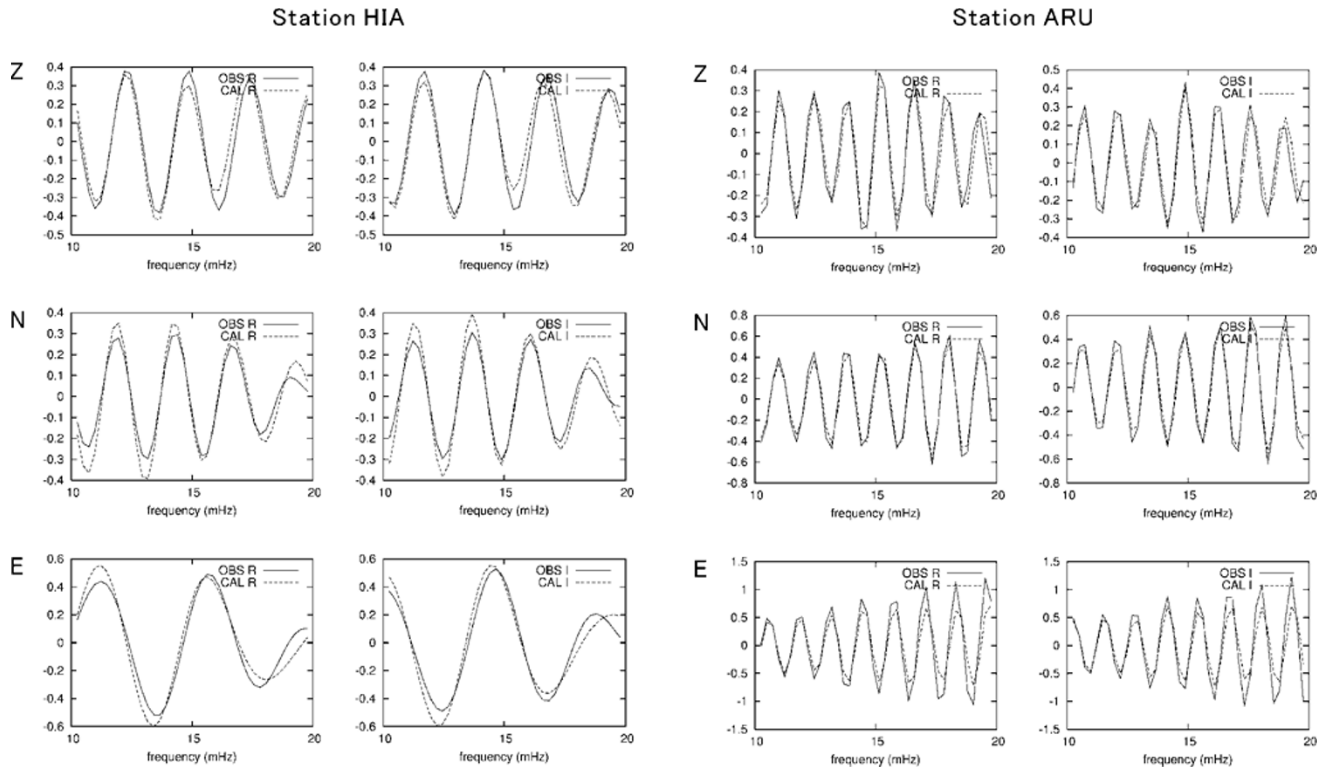


Fig. 3. Examples of the observed (solid curves) and synthetic (dashed curves) spectra of the vertical (top), NS (middle), and EW (bottom) components for stations HIA (Hailar, Neimenggu Province, China) and ARU (Arti, Russia). The left and right panels for each component show the real and imaginary parts of spectra, respectively.

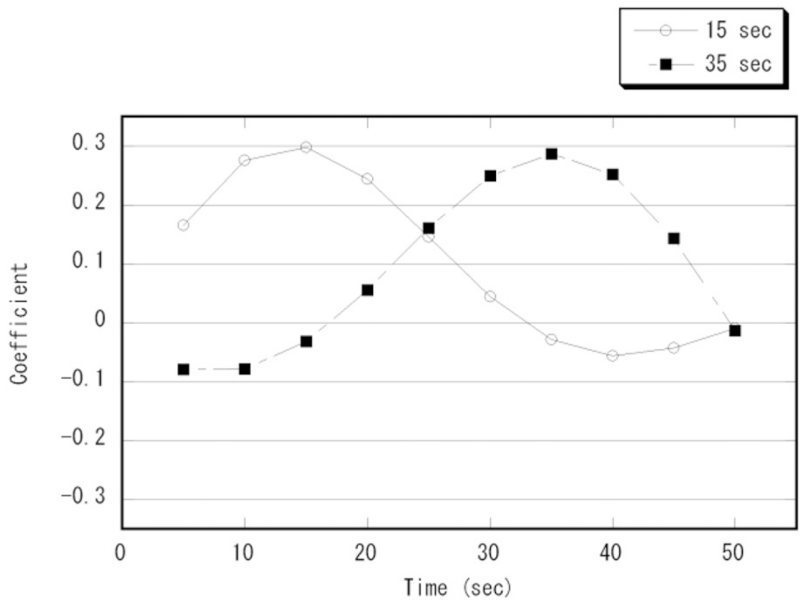


Fig. 4. The coefficients of the resolution matrix for the M_{rr} component (circles: the coefficients between the M_{rr} component at the time grid of 15 sec and those at 5–50 sec; squares: the coefficients between the M_{rr} component at the time grid of 35 sec and those at 5–50 sec).

in the source mechanism, while the thrust mechanism was dominant between 30–40 sec (Fig. 2(a)). The change of the source mechanism is shown more clearly in Fig. 2(b). For the first 20 sec, $M_{\phi\phi}$ is larger than M_{rr}, while the latter becomes larger than the former during 25–40 sec.

Figure 4 shows the coefficients of the resolution matrix for the M_{rr} component at the time grids of 15 and 35 sec (at the earlier grid the strike slip component is significant, while at the latter grid the thrust mechanism is predominant). The resolution for the other components is similar to that for the M_{rr} component. We show only the coefficients between M_{rr} components at the different time grids, since those between the different moment tensor components are negligible. The temporal resolution is about 20 sec ($\pm$10 sec). Thus, it is possible to detect such change of source mechanism as is shown in Fig. 2.

3. Discussion and Conclusions

We determined the temporal distribution of moment release of the main shock of the 2004 off the Kii peninsula earthquakes, in which the source mechanism changed during the rupture. Based on the resolution analysis, this change is reliable at least apparently.

We think that our result represents the actual change of the source mechanism for the following reasons. (i) The earth structure near the earthquake source region is not likely to be the cause, because its effect is not significant for seismic signals in the period range that we analyzed as Okamoto (1993) showed. (ii) The long wavelength three-dimensional earth structure and the structure just beneath seismic stations are not likely to produce the coherent scattered later arrivals for most of stations, which might produce an apparent change of source mechanism. (iii) We shifted the centroid location by 25 km in the north, south, east and west directions, respectively, and determined the temporal distribution. We found that the change of the source mechanism shown in Fig. 2 was a robust feature and not sensitive to the choice of centroid location.

The source mechanisms of some aftershocks were strike slip similar to that shown in Fig. 2(a) (http://www.jishin.go.jp/main/chousa/04sep_kiihantou2/p04-e.htm). As is shown in Fig. 1(a), there are two alignments of aftershocks (NW-SE and ENE-WSW), one of which (NW-SE) coincides with one of the nodal planes of the strike slip source mechanism. These observations suggest that the two fault planes with different orientations are related to Off-Kii peninsula earthquakes. In addition, the observed P waveforms can be well modeled when both thrust and strike slip source mechanisms are taken into account (http://iisee.kenken.go.jp/staff/yagi/eq/Japan20040905/new.html).

Based on our analysis, the above observations and discussions, we conclude that the main shock of the 2004 off the Kii peninsula earthquakes was a compound event consisting of the two different source mechanisms. Our conclusion is consistent with Hashimoto *et al.* (2005) who analyzed GPS data, and partly consistent with Baba *et al.* (2005) and Satake *et al.* (2005) who analyzed tsunami waveform data.

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