Tohoku 2011 earthquake, 11.03.2011, M_w = 9.1

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I. Main shock

At the first step inverting long period (from 300 s to 500 s) records of fundamental Love and Rayleigh modes we obtained parameters characterizing the event in point instant double-couple approximation: focal mechanism, seismic moment, and source depth. The records were processed by the frequency-time and polarization analysis package FTAN. We selected 20 Love wave records and 22 Rayleigh wave records of a good quality from IRIS, GEOSCOPE and GEOFON stations. Their azimuthal distribution is given in figure 1.

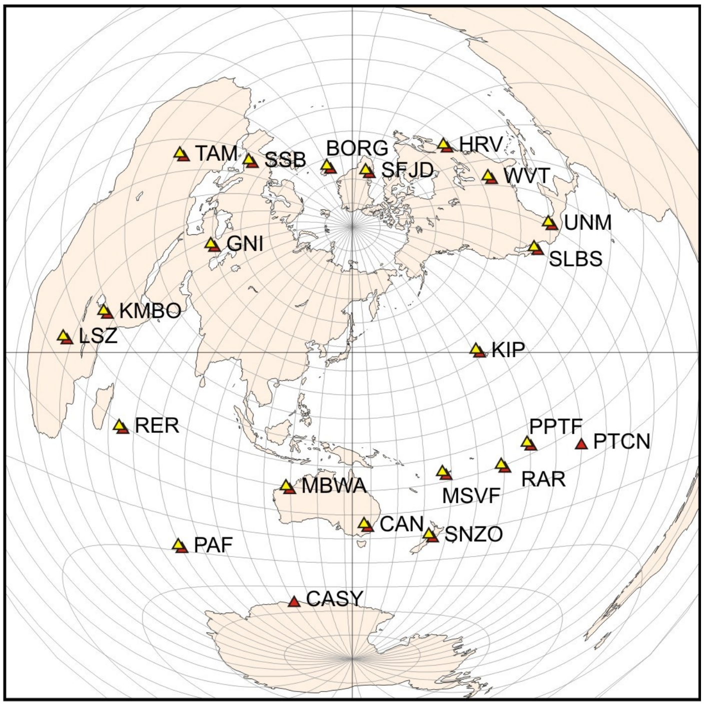

Fig. 1. Distribution of stations used for moment tensor inversion. Yellow triangles correspond to Love wave records, red triangles correspond to Rayleigh wave records.

Our solution gives a focal mechanism described by the following values of strike, dip and slip: 21°, 82°, 90° respectively (see figure 2). The estimated value of seismic moment is $0.51 \cdot 10^{23}$ Nm. This value corresponds to M_w = 9.1. Our estimate of best double-couple depth (10 - 20 km) is shown in figure 3.

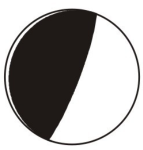

Fig. 2. Best double-couple obtained by inversion of long period surface wave spectra.

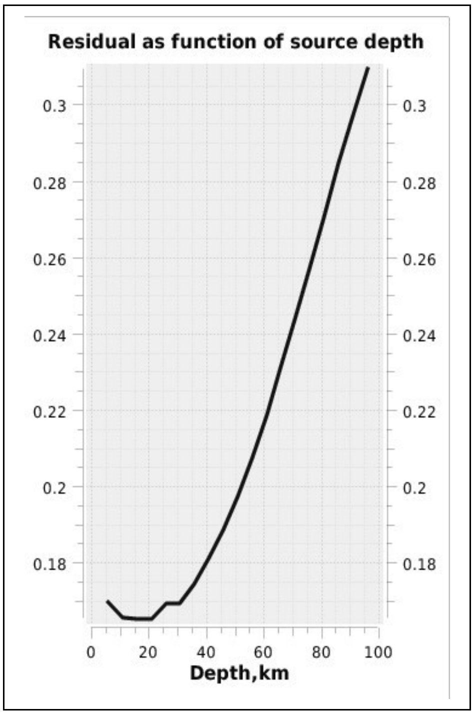

Fig. 3. Best double-couple depth residual function.

At the second step we estimated the 2-nd moments of moment tensor density. The nodal plane dipping to the West is considered as the fault plane. The focal mechanism is fixed at the values obtained in instantaneous point source approximation. The source depth and seismic moment are recomputed when determining the source 2nd-order moments. The final estimate of the depth is equal to 20 km counting from the free surface. Recalculated seismic moment is equal to $0.63 \cdot 10^{23}$ Nm. This value corresponds to $M_w = 9.1$.

The duration and the geometry of the source are estimated from the amplitude spectra of fundamental Love and Rayleigh modes in the period band from 200 to 300 seconds. We used the same records that were used for double-couple determination. The residual functions for the integral estimates of the source are given in figure 4.

We calculated the ranges of optimal values of these integral estimates as intervals where corresponding residual function exceeds the minimum residual value no more than by 5%. Calculated values are given in the table 1.

Duration, s	Major axis length, km	Minor axis length, km	Velocity, km/s	Lmax-strike angle, deg	Velocity-strike angle, deg
20 - 55	40 - 200	0 - 140	$\geq$ 0.6	0 - 75	15 - 60

Table 1. Results of inversion of 2-nd moments of moment tensor density.

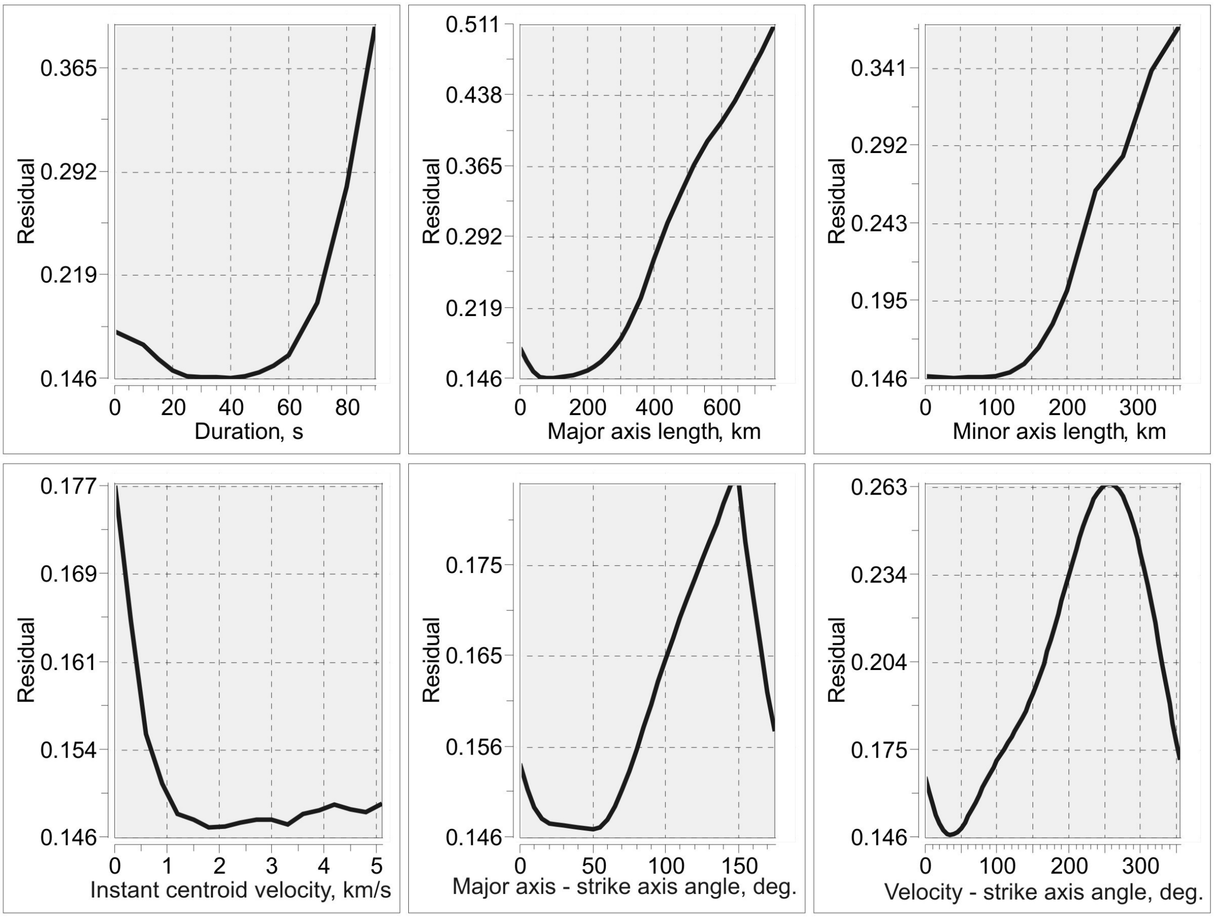

Fig. 4. Residual functions for integral estimates obtained for period band 200 - 300 s.

II. Foreshock, 09.03.2011, M_w = 7.5

Inverting long period (from 100 s to 200 s) records of fundamental Love and Rayleigh modes we obtained the optimal double-couple characteristics: focal mechanism, seismic moment, and source depth. The records were processed by the frequency-time and polarization analysis package FTAN. We selected 15 Love wave records and 19 Rayleigh wave records of a good quality from IRIS, GEOSCOPE and GEOFON stations. Their azimuthal distribution is given in figure 5.

We obtained following values of strike, dip and slip: 20°, 84°, 91° respectively (see figure 6). These values are very similar to those for the main shock. The estimated value of seismic moment is equal to $0.20 \cdot 10^{21}$ Nm. This value corresponds to M_w = 7.5. Our estimate of best double-couple depth (15 - 20 km) is shown in figure 7.

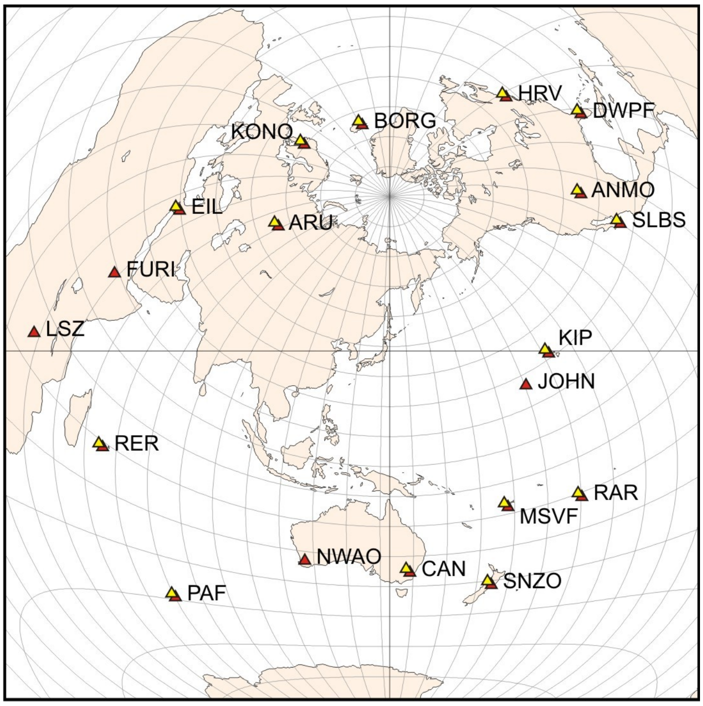

Fig. 5. Distribution of stations used for moment tensor inversion. Notations are as in figure 1.

Fig. 6. Best double-couple obtained by inversion of long period surface wave spectra.

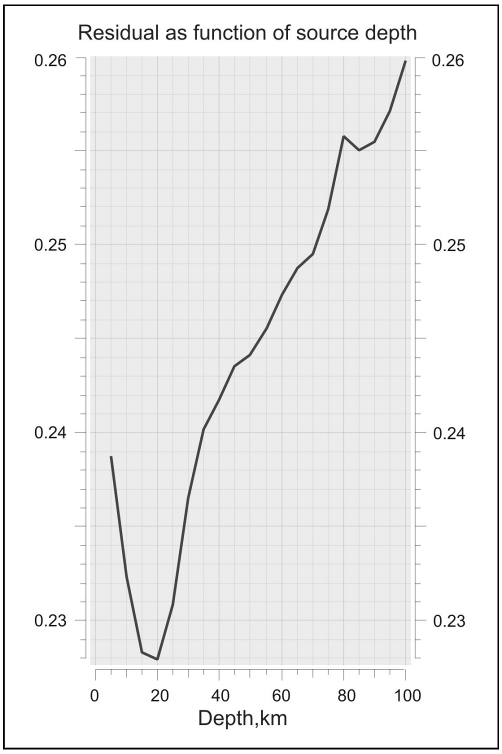

Fig. 7. Best double-couple depth residual function.

III. Strongest aftershock, 11.03.2011, M_w = 8.4

This aftershock occurred about half of an hour after the main shock. As a result the seismograms are very complicated by the presence of waves radiated by the preceding main shock. We filtered the seismograms by the frequency-time and polarization analysis package FTAN to isolate fundamental Love and Rayleigh modes in period band from 100 to 200 s. We selected 8 Love wave records and 12 Rayleigh wave records of a reasonable quality from IRIS, GEOSCOPE and GEOFON stations. Their azimuthal distribution is given in figure 8.

We obtained following values of strike, dip and slip: 33°, 89°, 91° respectively (see figure 9). These values are very similar to those for the main shock. The estimated value of seismic moment is equal to $0.46 \cdot 10^{22}$ Nm. This value corresponds to M_w = 8.4. Our estimate of best double-couple depth (10 km) is shown in figure 10.

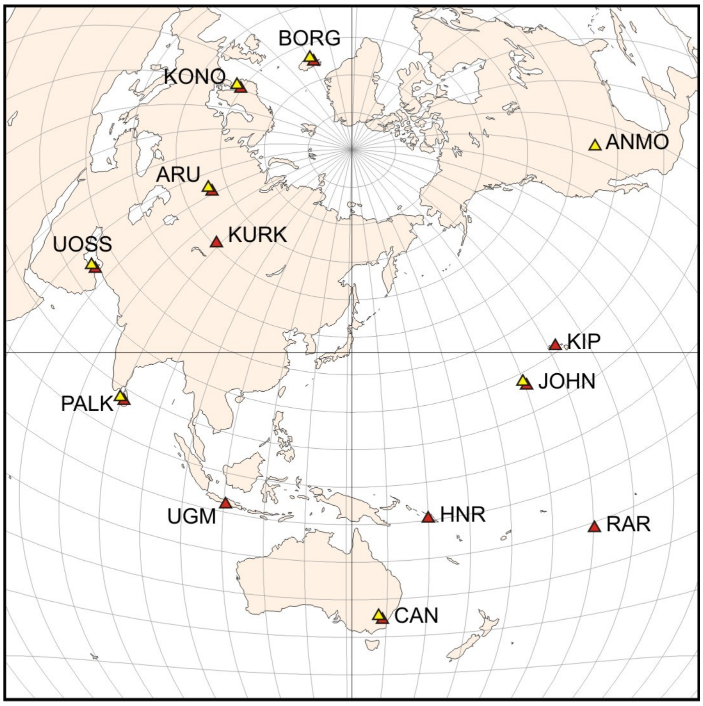

Fig. 8. Distribution of stations used for moment tensor inversion. Notations are as in figure 1.

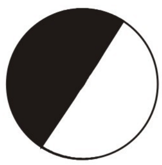

Fig. 9. Best double-couple obtained by inversion of long period surface wave spectra.

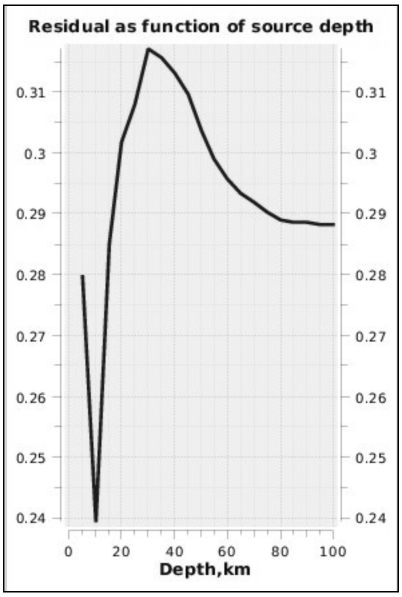

Fig. 10. Best double-couple depth residual function.

The minimum residual for the focal mechanism from the Global CMT catalog is by 32% larger than for our solution.

IV. Second in magnitude aftershock, 11.03.2011, M_w = 7.7

This aftershock occurred about ten minutes after the strongest aftershock. As a result the seismograms are very complicated by the presence of waves radiated by the preceding events. We filtered the seismograms by the frequency-time and polarization analysis package FTAN to isolate fundamental Love and Rayleigh modes in period band from 75 to 150 s. We selected 8 Love wave records and 8 Rayleigh wave records of a reasonable quality from IRIS, GEOSCOPE and GEOFON stations. Their azimuthal distribution is given in figure 11.

Inverting isolated long period (from 75 s to 150 s) amplitude spectra of fundamental Love and Rayleigh modes we obtained four equivalent double-couples radiating the same surface wave amplitude spectra. To select between these four an optimal double-couple we used polarities of direct P-waves. P waves radiated by this earthquake propagated on the background of seismic waves radiated by the preceding much stronger events. By this reason we picked up two polarities only. These polarities are not enough to distinguish between the solution above and those rotated by 180 degrees and multiplied by -1. We selected the optimal solution by analysis of surface wave phase spectra in period band from 100 s to 150 s.

We obtained following values of strike, dip and slip: 25°, 65°, -70° respectively (see figure 12). The estimated value of seismic moment is equal to $0.40 \cdot 10^{21}$ Nm. This value corresponds to M_w = 7.7. Our estimate of best double-couple depth (25 - 30 km) is shown in figure 13.

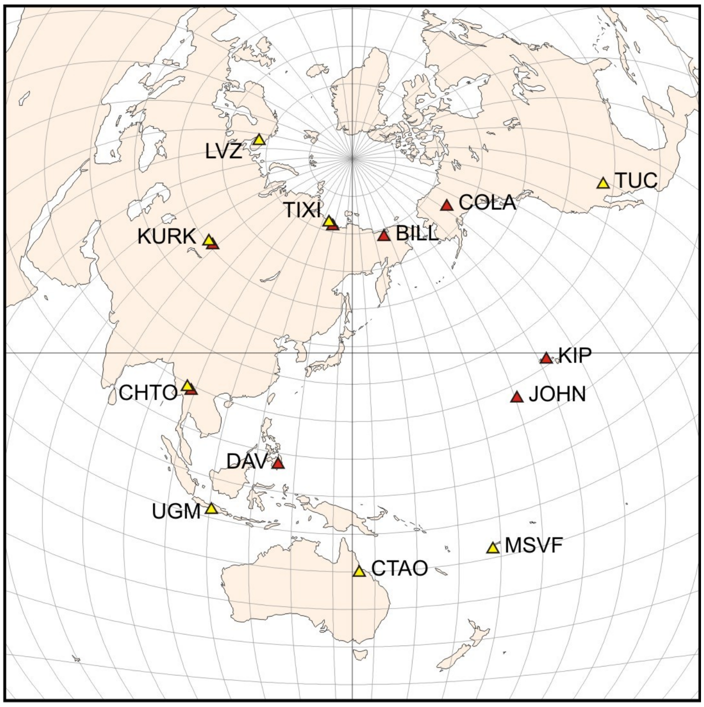

Fig. 11. Distribution of stations used for moment tensor inversion. Notations are as in figure 1.

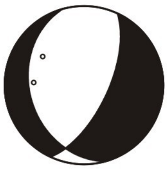

Fig. 12. Best double-couple obtained by joint inversion of long period surface wave spectra and P-wave polarities. Polarities are superimposed.

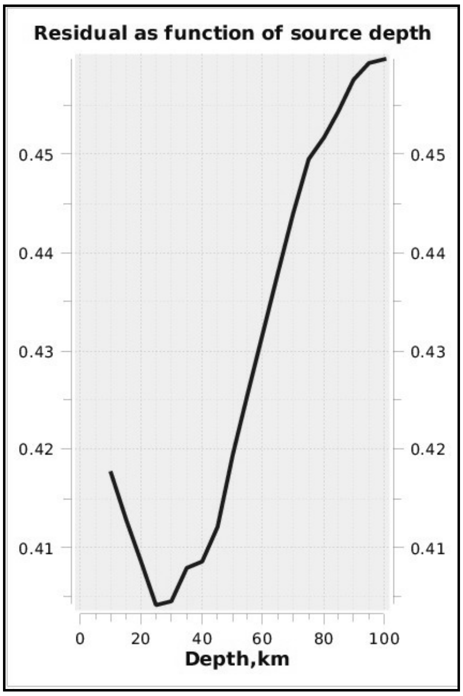

Fig. 13. Best double-couple depth residual function.

V. Comparison of different models of the main shock.

We calculated 2-nd moments for different models of the main shock and compared them with corresponding estimates obtained from surface wave inversion (see table 1). The results are presented in the table 2.

Models	Duration,s	Major axis length, km	Minor axis length, km	Velocity, km/s	Lmax-strike angle, deg	Velocity-strike angle, deg
Hayes	97	240	141	0.4	-7	87
Wei *et al.*	-	272	111	-	-5	-
Shao *et al.*	74	174	102	-	2	-
Satriano	69	210	157	-	37	-
SW inversion	20 - 55	40 - 200	0 - 140	$\geq$ 0.6	0 - 75	15 - 60

Table 2. Integral source characteristics of different source models.