Earthquake Research Institute International Programs Report: Hiroo Kanamori
Period of Stay at ERI: 11 September –November 17, 2008
Host Researcher: Prof. H. Kawakatsu

The main activity during my stay at ERI was the following.

1. Collaboration with Dr. Kawakatsu, Dr. Tsuruoka, JMA group, Dr. Nakano of NIED, and Dr. Ishida of JAMSTEC on W phase. With Dr. Luis Rivera who was visiting ERI at approximately the same time, we discussed how we can extend the W phase method to regional tsunami warning and rapid assessment of seismic hazard. Drs. Tsuruoka and Rivera have started a collaborative research which is expected to continue. We (Kanamori and Rivera) have written a paper on this for an international conference in Bali (Nov. 12-14, 2008). We performed preliminary tests on 8 large Japanese earthquakes using the Japanese F-net data. We showed that the W phase source inversion method can be used effectively for rapid and robust tsunami warning purposes, especially for very large earthquakes and slow tsunami earthquakes for which the traditional methods using relatively short period seismic waves are not effective. A copy of this paper is attached.

2. Discussion on tsunami excitation in special reference to the 2004 Sumatra earthquake. Discussions with Drs. Satake, Saito, Furumura, Fujii, and Watada were very productive in finding a clue to the discrepancy between seismic and tsunami models for this earthquake. Follow up analyses are still continuing.

Attachment

APPLICATION OF THE W PHASE SOURCE INVERSION METHOD TO REGIONAL TSUNAMI WARNING

HIROO KANAMORI[1], and LUIS RIVERA[2]

[1] Seismological Lab., California Inst. of Technology, Pasadena, CA USA
and Earthquake Research Institute, University of Tokyo, JAPAN, hiroo@gps.caltech.edu

[2] Institut de Physique du Globe de Strasbourg, CNRS-ULP, 5 rue Ren´e Descartes, Strasbourg Cedex, 67084 France
and Earthquake Research Institute, University of Tokyo, JAPAN, luis@eost.u-strasbg.fr

ABSTRACT: We earlier developed a fast seismic source inversion method using W phase with the aim at rapid tsunami warning. The main objective was to determine the seismic moment and the mechanism of large to great earthquakes at long period within 30 min after the origin time of an earthquake. Although the method was developed mainly for teleseismic tsunami warning purposes, when broad-band seismograms are available at regional distances (i.e., $\Delta \leq 12°$), we should be able to apply it for regional tsunami warning with minor modifications. We performed preliminary tests on 8 large Japanese earthquakes using the Japanese F-net data. We show that the W phase source inversion method can be used effectively for rapid and robust tsunami warning purposes, especially for very large earthquakes and slow tsunami earthquakes for which the traditional methods using relatively short period seismic waves are not effective.

1. INTRODUCTION

Kanamori and Rivera (2008) developed a source inversion method using the W phase with the aim toward rapid and reliable seismic tsunami warning. W phase is a long period phase arriving before S wave. It can be interpreted as superposition of the fundamental, 1st, 2nd, and 3rd overtones of spheroidal modes or Rayleigh waves and has a group velocity from 4.5 to 9 km/s over a period range of 100 to 1000 sec. The amplitude of long period waves better represents the tsunami potential of an earthquake. Because of the fast group velocity of W phase, most of W phase energy is contained within a short time window after the arrival of the P wave.

Here we summarize the method for teleseismic inversion.

1) Deconvolve the vertical component of global broadband seismic data to displacement with a pass-band of 0.001 Hz (1000 s) to 0.005 Hz (200 s). A time domain recursive method is used so that we can use a seismogram up to the point where it gets clipped at the large amplitude S or surface waves.

2) The W phase energy is mainly in the group velocity window of 4.5 to 9.0 km/s. Accordingly, we window the data for a duration of 15Δs (Δ in degree) from the beginning of P wave.

3) Compute synthetic W phases by normal mode summation. The normal modes and synthetic Green's functions are pre-computed and stored as a data base.

4) The observed and synthetic filtered and windowed waveforms are concatenated, and the concatenated time series are used for inversion.
5) Perform linear inversion using a given hypocenter location and the origin time. In the standard practice for rapid tsunami warning purposes, we use the hypocentral location determined by P waves, and the effective centroid time determined by grid search. For more detailed studies, the centroid location can be also determined by grid search.

In this paper we apply this method for inversion of regional broad-band records for rapid regional tsunami warning purposes.

2. APPLICATION TO REGIONAL DATA

Since the W phase includes the complete wave-field including both near- and far-field displacements, no major modification of the basic method is necessary for this application. However, in practice, we need to modify the method in three aspects:

1) With the windowing scheme described above, the duration of the data becomes too short at short distances. Thus, we use a constant window with a duration of $15\Delta_0$ where Δ_0 is a fixed distance, 12°. In this case the duration of the record is 180 s. The particular choice of Δ_0 is not critical, and a different choice can be used, if desired.
2) The records are often clipped very early at short distances; thus, we remove all the stations at distances shorter than 5°. Also, to determine the mechanism within a few minutes after the origin time, we cut off the distance range at 12°, which allows us to collect all the data for analysis within 6 min after the origin time. However, this distance range is adjustable depending on the station configuration and the requirements imposed by the local tsunami warning system.
3) For regional applications, we often need to determine the source mechanism of smaller earthquakes, to a magnitude of 6. Thus, we use, in addition to the standard frequency band, slightly shorter frequency bands, like 0.00167 Hz (600 s) to 0.005 Hz (200 s), or 0.002 Hz (500 s) to 0.01 Hz (100 s), depending on the noise level of the data available.

3. LARGE JAPANESE EARTHQUAKES

Since the Japanese F-net data are readily available through the Website of the National Research Institute for Earth Science and Disaster Prevention (NIED), we tested the method for 8 Japanese events. Table 1 lists the events we investigated. Figure 1 shows the epicenters of these events, and the F-net stations.

The 2003 Tokachi-oki earthquake is the largest of this data set. We first inverted the data using the hypocenter parameters (latitude, longitude, depth, origin time) reported by the Japan Meteorological Agency (JMA), and the centroid time, t_d, determined by grid search; the source half duration, t_h, is set equal to t_d. The result is shown in Figure 2, and Tables 2 and 3 (Solution 1). This inversion is very fast, and suitable for real-time tsunami warning purposes. The solution is similar to that of the Global CMT (GCMT) inversion, as shown in Figure 2, though M_w of the W phase inversion is slightly smaller. Figure 3 shows the fit of the observed concatenated W phase and that computed for this solution.

In the next step, we determined the centoroid location by a 2-dimensional grid search, with the depth being fixed at the original JMA. Figure 4 illustrates how the grid search is performed. Inversions are performed for each grid point as the centroid location and the root-mean-square (RMS) of the misfit is plotted on Figure 4. The grid point with the minimum RMS is taken for the centroid location. The solution (Solution 2), shown in Figure 2 and Tables 2 and 3 is similar to Solution 1. The smaller Mw is partly due to the large depth given by JMA. To see the effect of the depth, we inverted the data again by changing the depth from 45.1 km reported by JMA to 28.24 km reported by GCMT. The result is shown in Figure 2 and Tables 2 and 3 (Solution 3). The dip angle is decreased, and Mw increased by 0.1 unit. Although it would be generally desirable to determine the centroid location, the azimuthal coverage is very limited in our case because of the source-station geometry, and the centroid location determined by grid search may not be reliable.

For other events, we obtained two solutions, Solution 1 (JMA hypocenter with optimal t_d) and Solution 2 (with optimal t_d ($t_h = t_d$) and the centroid determined by grid search), and the solutions are listed in Tables 2 and 3. However, for these smaller events, the error in the centroid location may be larger than the rupture dimension of the source, and the significance of Solution 2 is questionable. Thus, we show only Solution 1 in Figure 5. The mechanisms and M_w are generally consistent with those of the GCMT solutions, and these solutions are useful for tsunami warning purposes.

4. DISCUSSION AND CONCLUSION

We have shown that the W phase source inversion method originally developed for teleseismic events can be used for inversion of regional events with only minor modifications. The teleseismic and regional applications are different in 3 aspects: 1) Because of the short distances, the windowing scheme has to be modified. 2) At short distances the structure we are using (i.e., PREM, Dziewonski and Anderson, 1981) may not be adequate. The travel times computed with PREM are different from the actual travel times, but these differences are absorbed in t_d. If further improvement is desired, a more appropriate 1-D structure will have to be used for computing the Green's functions. Ideally, a 3-D structure may be needed, but the present accuracy is probably adequate for tsunami warning purposes. 3) Because of the limited azimuthal coverage for the source-station geometry for the Japanese events, the grid search of the centroid location does not yield a meaningful result for moderate-size earthquakes (i.e. M_w =<7.5). At present, attempts to determine the centroid should be limited to only very large events (i.e., M_w > 7.5). For other regions, the source-station geometry can be more favorable for centroid determination by grid search.

The maximum distance used is 12° which means that we can collect all the data necessary for inversion in 6 min. Since the execution of the program is done very fast without any human intervention, the source mechanism and the magnitude can be obtained very rapidly. Despite the limitations we discussed above, we believe that the W phase source inversion method can be used effectively for rapid and robust tsunami warning purposes, especially for very large earthquakes and slow tsunami earthquakes for which the traditional methods using relatively short-period seismic waves are not effective.

5. ACKNOWLEDGMENTS

This work was carried out while both HK and LR were staying at the Earthquake Research Institute of the University of Tokyo under the International Earthquake and Volcano Research Promotion Program. We acknowledge that all the broad-band seismograms used in this study are provided by the F-net of the National Research Institute for Earth Science and Disaster Prevention (NIED).

6. REFERENCES

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Global CMT catalog; GCMT. http://www.globalcmt.org

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Table-1. List of the earthquakes studied. The origin time (UT), latitude, longitude, and depth are taken from the JMA catalog. M_w is from the GCMT solutions.

Event	**Date**	**Origin time**	M_w	**Lat. (°)**	**Long. (°)**	**Depth (km)**
2003 Miyagi-oki	5/26/2003	9:24:33.42	6.99	38.821	141.651	72.0
2003 Tokachi-oki	9/25/2003	19:50:7.42	8.26	41.77	144.078	45.1
2004 Kii-1	9/5/2004	10:07:07.50	7.19	33.033	136.79	37.6
2004 Kii-2	9/5/2004	14:57:16.81	7.37	33.138	137.141	43.50
2008 Ibaraki	5/7/2008	16:45:18.77	6.85	36.228	141.608	50.6
2008 Iwate	6/13/2008	23:43:45.36	6.89	39.030	140.881	7.8
2008 Fukushima	7/19/2008	2:39:28.69	6.92	37.521	142.364	31.6
2008 Miyagi-Iwate	7/23/2008	15:26:19.69	6.77	39.732	141.635	108.1

Table-2. Centroid parameters used for W-phase inversion

Event	**Inversion**	**θ_s (°)**	**λ_s (°)**	**d_s (km)**	**t_d (s)**	**t_h (s)**
2003 Tokachi-Oki	1. JMA+optimized t_d	41.779	144.078	45.1	23.8	23.8
	2.optimized t_d and centroid	41.91	144.14	45.1	23.8	23.8
	3. with CMT depth	42.21	143.84	28.24	23.8	23.8
2003 Miyagi-oki	1. JMA+optimized t_d	38.821	141.651	72.0	9.4	9.4
	2.optimized t_d and centroid	38.32	141.91	72.0	9.4	9.4
2004 Kii-1	1. JMA+optimized t_d	33.030	136.798	37.6	11.2	11.2
	2. optimized t_d and centroid	33.030	136.798	37.6	11.2	11.2
2004 Kii-2	1. JMA+optimized t_d	33.138	137.141	43.50	31.65	31.65
	2. optimized t_d and centroid	32.86	137.68	43.50	31.65	31.65
2008 Iwate	1. JMA+optimized t_d	39.03	140.881	7.8	3.6	3.6
	2. optimized t_d and centroid	38.86	141.18	7.8	3.6	3.6
2008 Fukushima	1. JMA+optimized t_d	37.521	142.364	31.6	11.1	11.1
	2. optimized t_d and centroid	37.91	142.09	31.6	11.1	11.1
2008 Miyagi-Iwate	1. JMA+optimized t_d	39.732	141.635	108.1	3.4	3.4
	2. optimized t_d and centroid	39.640	141.640	108.1	3.4	3.4
2008 Ibaraki	1. JMA+optimized t_d	36.228	141.608	50.6	15.9	15.9
	2. optimized t_d and centroid	36.368	141.648	50.6	15.9	15.9

Table-3. W-phase inversion solutions

Event	**Inversion**	**Nodal plane-1 (strike/dip/rake)**	**Nodal plane-2 (strike/dip/rake)**	M_w
2003 Tokachi-Oki	1. JMA+optimized t_d	33.3/73.8/73.6	259.8/22.9/134.2	8.00
	2.optimized t_d and centroid	32.9/68.6/72.8	253.2/27.2/127.1	7.97
	3. with CMT depth	34.2/76.5/80.9	248.6/16.2/123.3	8.10
2003 Miyagi-oki	1. JMA+optimized t_d	338.9/27.0/57.1	194.8/67.6/105.5	6.98
	2.optimized t_d and centroid	348.9/27.9/64.4	197.3/65.1/102.9	6.97
2004 Kii-1	1. JMA+optimized t_d	287.7/36.5/116.0	76.5/57.7/72.1	7.25
	2. optimized t_d and centroid	303.9/42.9/144.7	61.3/66.8/52.9	7.27
2004 Kii-2	1.JMA+optimized t_d	239.5/53.4/34.1	127.5/63.3/138.1	7.51
	2. optimized t_d and centroid	239.7/48.2/24.5	132.7/72.0/135.5	7.55
2008 Iwate	1.JMA+optimized t_d	7.4/43.3/92.1	184.5/46.7/88.0	6.71
	2. optimized t_d and centro	12.9/40.2/90.0	192.9/49.8/90.0	6.75
2008 Fukushima	1.JMA+optimized t_d	197.8/14.2/79.3	28.8/76.1/92.7	6.95
	2. optimized t_d and centro	222.4/29.6/124.7	3.9/66.0/72.1	6.86
2008 Miyagi-Iwate	1.JMA+optimized t_d	21.3/16.7/-84.1	195.2/73.4/-91.8	6.89
	2. optimized t_d and centroid	12.7/16.7/-90.8	193.5/73.3/-89.8	6.86
2008 Ibaraki	1.JMA+optimized t_d	206.8/23.2/92.5	24.1/66.8/88.9	6.80
	2. optimized t_d and centroid	208.4/22.2/99.7	17.9/68.2/86.1	6.79

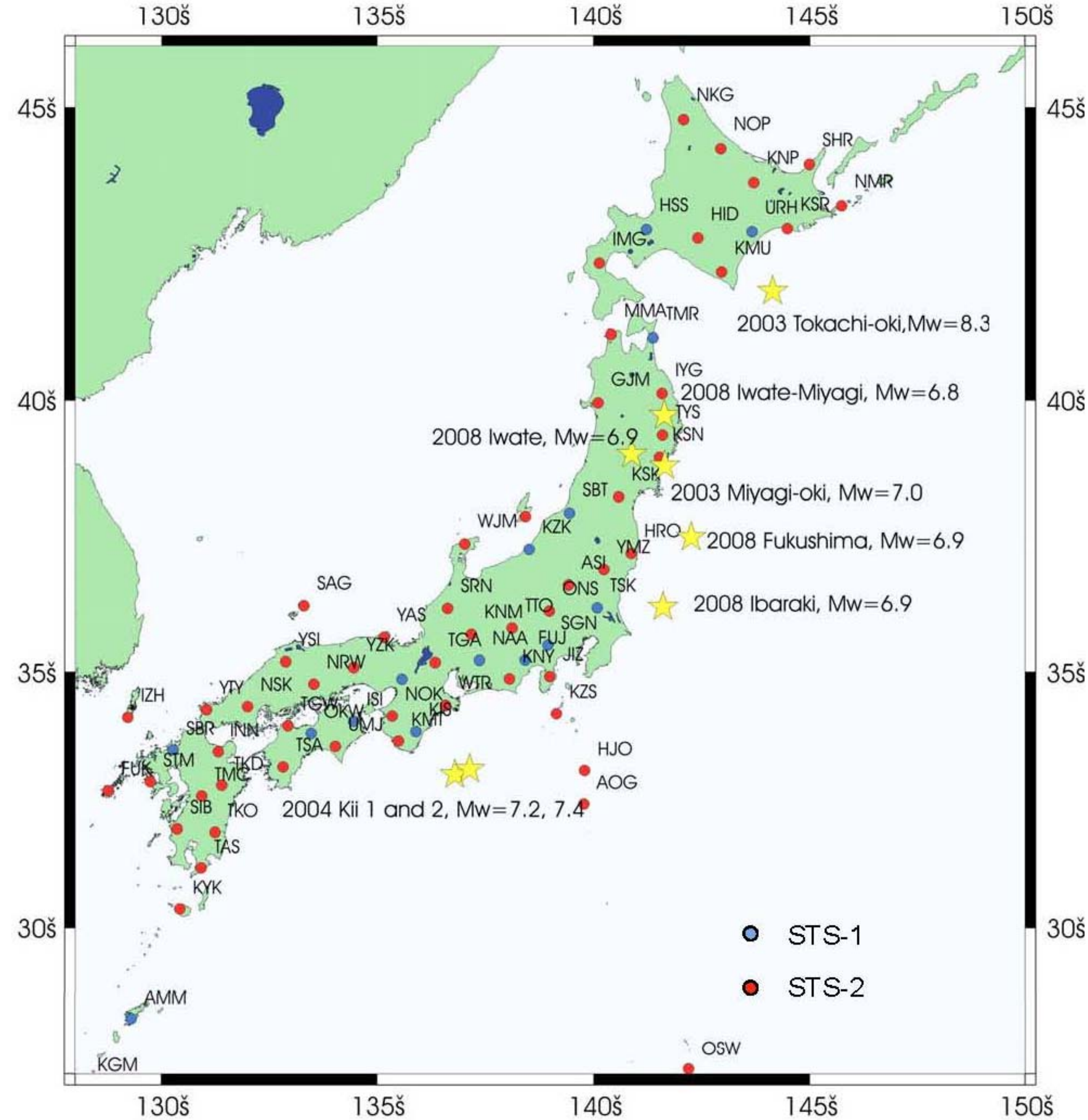

Figure 1. Epicenters of the events studied and the distribution of F-net stations.

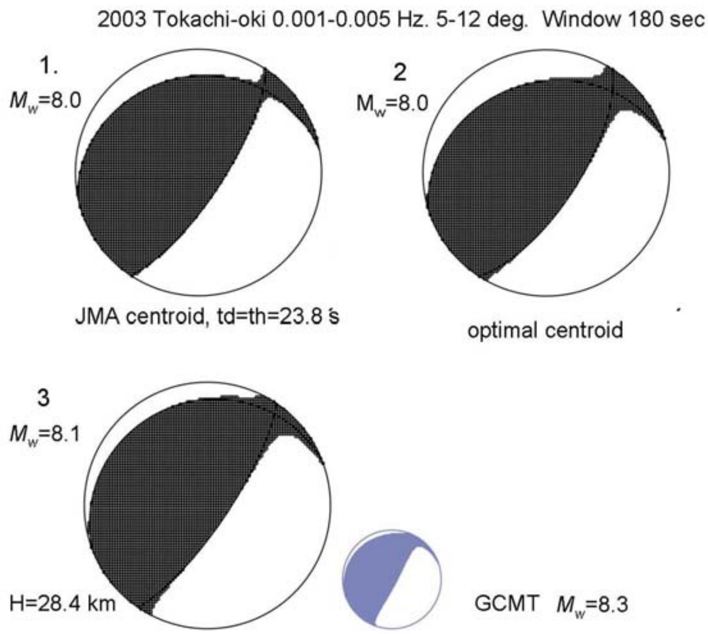

Figure 2. W-phase inversion solutions for the 2003 Tokachi-Oki earthquake.
1. JMA location with optimal t_d. 2. Optimal centroid and t_d. 3. Solution 2 with H=28.24 km. The GCMT solution is shown in blue.

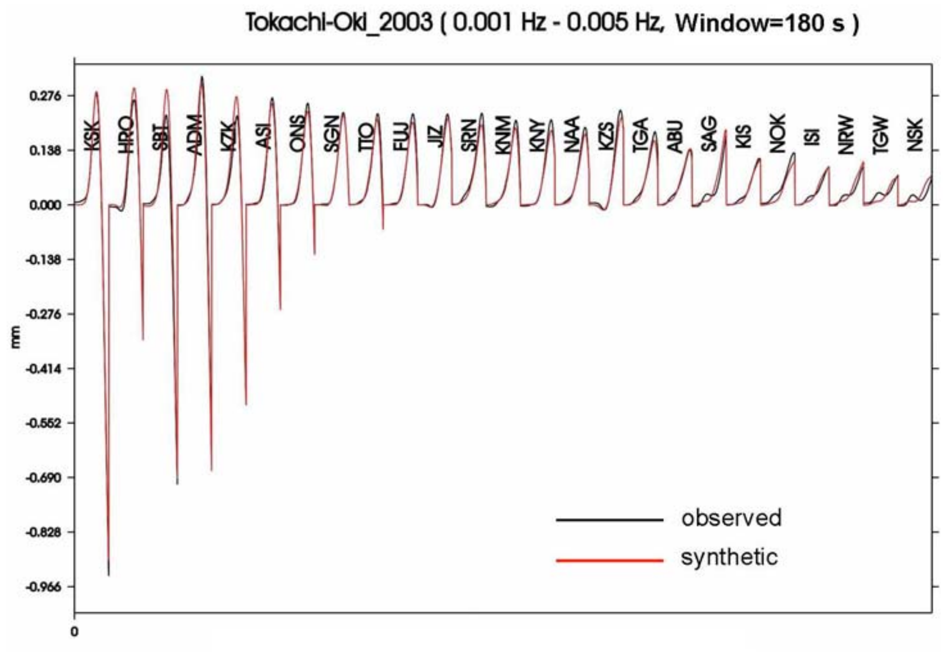

Figure 3. Comparison of the observed concatenated W phase with that computed for Solution 1.

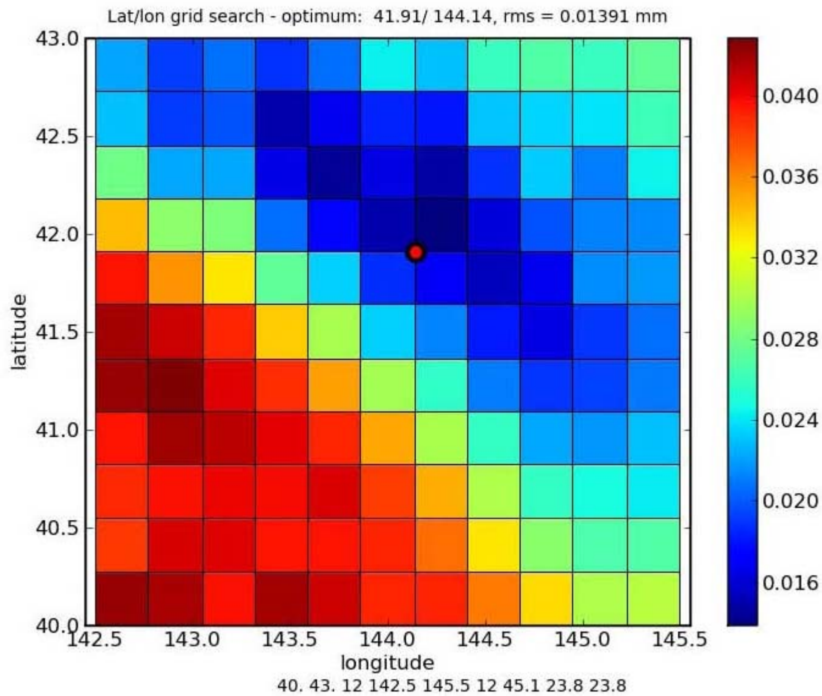

Figure 4. The distribution of RMS misfit. The RMS value in the box corresponds to the grid point on the lower-left corner of the box. The unit of the RMS residual is mm.

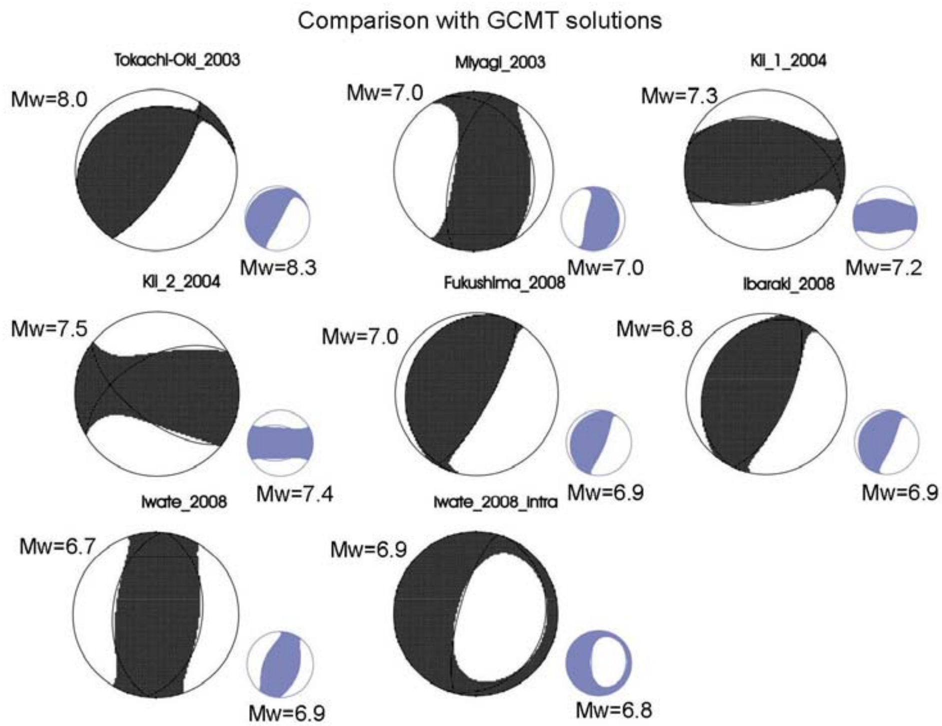

Figure 5. Comparison of Solution 1 with the GCMT solutions.