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Key Points:

- We have developed an automatic system for finite-fault inversion based on the iterative deconvolution and stacking (IDS) technique
- Offline tests demonstrate that the rupture models can be well estimated when the strong-motion data and the mechanism solution are available
- Integration of the automatic finite-fault inversion in a rapid response and early warning system is realistic for regions like Japan

Supporting Information:

- Supporting Information S1
- Data Set S1
- Data Set S2

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Automatic Inversions of Strong-Motion Records for Finite-Fault Models of Significant Earthquakes in and Around Japan

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Abstract Automatic and rapid imaging of earthquake rupture process is a difficult task but critical for postearthquake response and possible tsunami early warning. We have developed an automatic system for finite-fault inversion based on the iterative deconvolution and stacking (IDS) approach, in which we screen the waveforms and update the fault size automatically. Strong-motion seismograms are used in offline tests to invert for the rupture processes of 34 significant earthquakes in 2008–2017 in and around Japan with magnitudes $M_W \geq 6.0$ occurred onshore and $M_W \geq 6.5$ offshore. Rupture model of an earthquake, including moment magnitude, source time function, slip distribution, rupture velocity, and stress drop, is obtained in ~ 1.5 min on a desktop PC. The moment magnitudes we obtained are consistent with those published by other agencies. The slip distributions, rupture directions, and velocities also agree well with those released by the Japan Meteorological Agency. In all test cases, our results show that the automatic inversion of strong-motion data can provide reliable major source parameters without manual revision, which demonstrates great potential for emergency response and tsunami early warning purposes. The automatic inversion system developed in this work can also be used to build catalogs of finite-fault models for moderate to strong earthquakes in other areas where the moment tensor solutions and near-field waveform data are available.

1. Introduction

Recent advances in high-density seismic networks, communications technologies, data processing, and real-time seismology have led to successful practical operations of earthquake early warning (EEW) systems in many parts of the world, including Europe, Japan, California, and Taiwan (Allen et al., 2009; Kanamori et al., 1997). EEW systems model earthquakes as point sources, estimate the magnitudes and locations by using the waveform records within the first few seconds, and predict the ground motion intensities and tsunami heights. Such EEW systems work well for earthquakes of magnitude $M_W = 6.0$ and lower with relatively small fault ruptures (Böse et al., 2012). However, for large earthquakes, the fault rupture can extend as long as several hundred kilometers, and the spatial pattern of strong ground motion can be greatly influenced by the earthquake source process, such as the rupture directivity and slip distribution (Kanamori, 2008; Kuge, 2003). Therefore, most current EEW systems tend to underestimate the magnitudes of large earthquakes since they do not take into account the finite sizes of the faults, leading to underestimations in ground motion intensities and tsunami heights.

A typical example is the 11 March 2011 M_W 9.0 Tohoku earthquake. The Japan Meteorological Agency (JMA) issued the first warning of a magnitude 7.2 quake 31 s after the origin time and then updated to 8.1 at 127 s (http://www.data.jma.go.jp/svd/eeew/data/nc/pub_hist/2011/03/20110311144640/content/content_out.html; last accessed: 17 July 2020). Based on the estimated magnitude of 8.1, JMA issued warnings of tsunami heights of 6 m in Miyagi Prefecture and of 3 m in Iwate and Fukushima Prefectures (Monastersky, 2012). However, the actual heights of tsunami waves reached 40 m in Iwate and 15 m in Miyagi and Fukushima (Mori et al., 2011). The tsunami flooded the Fukushima Daiichi nuclear plant, leading to a Level 7 nuclear meltdown and the release of radioactive materials (Amagai et al., 2014). As of June 2020, the National Police Agency of Japan had confirmed 15,899 deaths caused by the disaster (National Police Agency of Japan, 2020), in which 92.5% can be attributed to the tsunami (Fritz et al., 2012).

Although the JMA early warning system is arguably the most advanced in the world, its tsunami warning after the 2011 Tohoku earthquake was deemed a failure (Cyranoski, 2011a; Listed, 2012). Several studies have been devoted to find out the reasons for this failure. An important conclusion is that the JMA EEW system uses local broadband seismographs and a relatively narrow frequency range, causing saturation in magnitude estimation. On the other hand, it assumes a single point source, which does not account for the fault finiteness, causing underestimation of intensity and larger uncertainty in tsunami height estimation (Cyranoski, 2011b; Hoshiba & Iwakiri, 2011; Hoshiba & Ozaki, 2014; Listed, 2012; Monastersky, 2012).

Rapid imaging of finite-fault rupture models, that is, spatial and temporal slip distributions, can significantly enhance the accuracy in strong ground motion forecasts and tsunami hazard assessments for large earthquakes. With the recent advancements in digital seismology and computational techniques, a number of algorithms for rapid source inversion have been developed. Izutani and Hirasawa (1987) proposed a method to quickly determine the fault lengths and rupture directions of large shallow earthquakes using accelerograms. To improve the efficiency, several techniques to estimate the rupture extent were then developed for real-time purposes (Convertito et al., 2012; Lomax, 2005; Yamada et al., 2007; Yamada & Heaton, 2008; Yamada, 2014). These efforts are helpful for assessing the fault dimensions but are still insufficient for quantitative tsunami simulation since the detailed fault slips, for example, peak slip, slip variations along strike and dip, are not considered. Finite-fault models are ideal for ground motion predictions and tsunami simulations. Although numerous algorithms have been developed in the past few decades (e.g., Hartzell & Heaton, 1983; Ji et al., 2002; Olson & Apsel, 1982; Wang et al., 2008; Yagi & Fukahata, 2011a; Zhang et al., 2012), most of them depend on manual operations and are mainly designed for research purposes, not for automatic and real-time analysis. Efforts have been made to integrate these techniques into practical automatic systems with some success (Dreger et al., 2005; Dreger & Kaverina, 2000; Koch et al., 2019; Kuge, 2003). But manual operations are needed at present to obtain a reasonable rupture model in most cases, which usually takes several hours. In recent years, W-phase slip inversions have been automated and can obtain a model ~25 min after the earthquake, which is suitable for early warning at regional and teletsunami distances (Benavente et al., 2016). On the other hand, devastating tsunamis caused by large offshore earthquakes can reach the coastal regions within 10 to 30 min (e.g., the 2004 Sumatra and 2011 Tohoku earthquakes). Therefore, previous seismological techniques are not fast enough to provide slip models for tsunami early warning, particularly at the nearest coast.

In a more recent development, displacements measured from Global Navigation Satellite Systems (GNSS) have been used to obtain the fault slip model based on the elastic dislocation theory. In particular, the inversion is relatively straightforward compared to seismic waveform inversion and is easier to be automated. With the real-time GNSS displacement data, Ohta et al. (2012) estimated the magnitudes as well as the fault sizes and the uniform slips on rectangular fault planes for large earthquakes ($M > 8$). This work led to better estimation of magnitude, but the uniform-slip model is still too simple for tsunami wave height prediction. For example, Sobolev et al. (2007) pointed out that even with the same seismic moment, different slip distributions may lead to tsunami wave heights with differences of 5 times more. To obtain slip models with more practical details, Wright et al. (2012) and Colombelli et al. (2013) divided the fault into several rectangular patches along the strike and derived the slips of each patch by inverting the GPS displacements. Other studies tried to determine the slip distributions by restricting the rupture on a predefined fault plane or a subducting plate (Crowell et al., 2012; Hoechner et al., 2013; Kawamoto et al., 2015). Minson et al. (2014) utilized the Bayesian inference to solve for the fault geometry and the finite-fault slip distribution in near real time with a few prior constraints. Furthermore, to enhance the earthquake and earthquake-induced tsunami early warning capabilities, Kawamoto et al. (2017) developed a real-time system based on the GNSS Earth Observation Network (GEONET), including real-time GNSS positioning, automatic coseismic deformation monitoring, and near real-time slip inversion.

It is worth noting that GNSS-based inversion procedures involve the waveform and static slip approaches. The former is identical to the seismic waveform inversion (Melgar & Bock, 2015; Yue & Lay, 2011). It requires a highly automated finite-fault inversion technique to meet the requirement of emergency responses. Therefore, many GNSS-based inversion procedures are static approaches neglecting the dynamic effects on surface deformation. The displacement data used in the inversions are extracted from the continuous GNSS data and are updated every second during the ongoing ruptures. They are treated then as

Figure 1. Tectonic setting around Japan and target earthquakes used in this study. Magenta and green beach balls show the focal mechanisms of inland and offshore events, respectively, with magnitudes indicated by the size of the beach balls. The earthquake catalog is listed in Table 1. Gray barbed lines represent the plate boundaries. Thick white arrows represent the subduction direction of the Pacific and Philippine Sea plates. The blue box depicted in the inset map shows the location of the detailed region.

quasistatic surface deformation caused by the transient fault dislocation. Therefore, the inversion cannot yield the rupture history directly and may underestimate the effect of rupture directivity. In addition, except in Japan, GNSS stations at present are not widely deployed. In contrast, strong-motion networks are more common in many earthquake-prone regions. Although strong-motion data have been used in source studies since the 1980s (Hartzell & Heaton, 1983; Olson & Apsel, 1982), they have not been widely used in automatic inversions of finite-fault rupture processes.

Zhang et al. (2014) developed an iterative deconvolution and stacking (IDS) method to automatically determine the finite-fault models. Based on the near-field waveform seismograms and fault model, the IDS method can estimate a rake-fixed rupture model through stacking of the deconvolved sub-fault apparent source time functions. The deconvolutions and stackings in the IDS method can be performed without any manual intervention and thus is highly adaptable to automation. The feasibility and efficiency of the IDS method have been investigated in several practical cases (Diao et al., 2016; Zhang et al., 2015, 2020; Zheng et al., 2017, 2018). However, these applications of the IDS method are still based on previously selected and processed waveform records, and a preassumed fault plane with certain size and discretization. These factors may affect the finite-fault model and thus should be considered in automatic inversions. In this study, we first develop an automatic system for finite-fault inversion based on the IDS method. We then demonstrate the performance of the automatic system using the strong-motion records of 34 significant earthquakes ($M_w \geq 6.0$ and $M_w \geq 6.5$ for inland and offshore events, respectively) in and around Japan in 2008–2017 (see Figure 1). Finally, we discuss the prospect of applications of the automatic system for rapid postearthquake response and tsunami early warning.

2. Data Processing and Automatic Inversion Scheme

Japan is a seismically active area. From the centroid moment tensor (CMT) catalog released by JMA, there are 34 shallow-focus earthquakes occurred during 2008 and 2017 with magnitudes $M_w \geq 6.0$ onshore or $M_w \geq 6.5$ offshore (Figure 1 and Table 1). These events were recorded by the strong-motion networks

Table 1
Source Parameters of the 34 Earthquakes Used in This Study

No.	Origin time (JST)	Longitude (°E)	Latitude (°N)	Depth (km)	M_W	φ_1	δ_1	λ_1	φ_2	δ_2	λ_2
1	2008/05/08 01:45	141.61	36.23	27	6.8	209	19	94	25	71	89
2	2008/06/14 08:43	140.88	39.03	8	7	176	47	58	38	51	120
3	2008/07/19 11:39	142.26	37.52	22	6.9	202	20	85	28	70	92
4	2008/09/11 09:20	144.15	41.78	31	6.7	228	21	120	16	72	79
5	2009/08/11 05:07	138.50	34.79	23	6.3	73	64	28	330	65	151
6	2009/08/13 07:48	140.83	32.87	53	6.5	69	25	149	187	78	68
7	2010/03/14 17:08	141.82	37.72	32	6.5	189	21	80	20	69	94
8	2011/03/09 11:45	143.28	38.33	19	7.3	187	11	75	22	79	93
9	2011/03/11 14:46	142.86	38.10	24	9	193	10	79	24	81	92
10	2011/03/11 15:08	142.77	39.82	32	7.4	187	10	74	23	80	93
11	2011/03/11 15:15	141.25	36.12	43	7.7	200	29	90	20	61	90
12	2011/03/11 15:25	144.75	37.91	19	7.5	184	43	−103	22	49	−78
13	2011/03/12 03:59	138.60	36.99	8	6.3	60	31	110	216	61	78
14	2011/03/15 22:31	138.71	35.31	9	6	31	78	42	290	49	164
15	2011/03/22 16:18	144.25	37.09	11	6.5	209	29	−105	45	62	−82
16	2011/04/07 23:32	141.92	38.20	66	7.1	24	37	87	207	54	92
17	2011/04/11 17:16	140.67	36.95	6	6.7	150	53	−96	341	38	−82
18	2011/04/21 22:37	140.69	35.68	41	6.2	204	29	106	6	62	82
19	2011/06/23 6:50	142.59	39.95	33	6.7	145	28	47	12	70	110
20	2011/07/10 09:57	143.51	38.03	34	7	67	74	7	335	84	164
21	2011/09/17 04:26	143.09	40.26	25	6.6	172	17	57	26	76	99
22	2012/03/14 18:08	145.23	40.78	12	6.9	276	42	−81	84	48	−98
23	2012/12/07 17:18	143.87	38.02	28	7.3	217	14	−76	22	77	−93
24	2013/10/26 02:10	144.57	37.20	56	7.1	169	35	−115	19	59	−73
25	2014/07/12 04:22	142.32	37.05	13	6.5	188	23	−92	10	67	−89
26	2014/11/22 22:08	137.89	36.69	5	6.2	18	58	59	246	43	129
27	2015/02/17 08:06	143.19	39.87	23	6.7	177	13	62	26	79	96
28	2015/05/13 06:12	142.15	38.86	35	6.8	160	29	47	27	69	110
29	2016/01/14 12:25	142.80	41.97	52	6.7	226	22	109	26	69	83
30	2016/04/14 21:26	130.81	32.74	11	6.2	31	80	−169	299	79	−10
31	2016/04/15 00:03	130.78	32.70	8	6	211	63	−178	120	88	−27
32	2016/04/16 01:25	130.76	32.75	12	7	222	85	177	312	87	5
33	2016/10/21 14:07	133.85	35.38	6	6.2	339	90	−10	69	80	−180
34	2016/11/22 05:59	141.60	37.35	9	6.9	65	55	−69	212	40	−117

Note. φ , δ , and λ are strike, dip, and rake angles in degrees. Dates are formatted as YYYY/MM/DD.

K-NET and KiK-net operated by the National Research Institute for Earth Science and Disaster Resilience (NIED). The two networks consist of more than 1,700 stations deployed at a 20–25 km interstation spacing all over Japan (Aoi et al., 2011). Most K-NET stations are installed on the free surface in public offices, schools, and parks. On the contrary, the KiK-net station includes a pair of strong-motion sensors installed on the free surface as well as in a borehole, and they are located in relatively quiet places to reduce nonseismic noise. Furthermore, these densely and almost uniformly distributed strong-motion instruments operate with real-time data transmission and large dynamic range, which gives us a great opportunity to develop and test rapid automatic algorithms. To reduce the impact of site effect and urban noise as much as possible, we use the three-component records of the borehole sensors in this study. All waveform components were equally weighted in inversions.

To achieve reliable results, we need to choose stations with suitable distances from the source. Zhang et al. (2015) concluded that a dense network of strong-motion stations whose distances from the source are 2 to 3 times of the rupture dimension can provide reliable image of the rupture. In this study, we use stations with distances up to 3 times the fault length, where the fault length can be roughly estimated from the preliminary magnitude estimate based on the empirical scaling law of Wells and Coppersmith (1994). Meanwhile, we limited the maximum number of stations to 40. In case that more than 40 stations are available for an earthquake, we reselect the stations with a larger interstation spacing.

The acceleration seismograms were integrated twice into displacement time series. This double numerical integration may amplify the drift caused by baseline shifts that are mainly induced by the ground tilting.

Table 2
Subfault Sizes and Frequency Bands Based on Earthquake Magnitudes Used in Automatic Inversions in This Study

M_W	Subfault size (km)	Frequency band (Hz)
$5.5 \leq M_W < 6.5$	2	0.02–0.5
$6.5 \leq M_W < 7.5$	5	0.02–0.2
$7.5 \leq M_W < 8.5$	10	0.02–0.1
$8.5 \leq M_W < 9.5$	20	0.02–0.05

The long-period drifts can be corrected by empirical operations (e.g., Wang et al., 2011). For simplification, we apply a high-pass filter (with fixed lower cutoff frequency of 0.02 Hz) to the displacement waveforms. Note that this operation can be also used in real-time operations with incomplete waveforms. On the other hand, a low-pass filtering of the data is necessary, too. The upper cutoff frequency is mainly associated with the subfault size; that is, the minimum wavelength should be much larger than the subfault size to satisfy its point-source assumption. Here,

we use the approximate formulae $f_{cut} \sim \frac{1}{4} \frac{V_s}{\Delta L}$ to set the upper cutoff

frequency, where V_s is the S -wave velocity and ΔL is the subfault size (Heimann, 2010). The subfault size and upper cutoff frequency are both dependent on the earthquake magnitude (see Table 2).

Due to possible instrument malfunctions and strong local site effects, some of the records contain waveform anomalies that are not related to the source. Therefore, we cannot invert all the records directly for the finite-fault rupture. Zheng et al. (2018) proposed a strategy to address this problem by dividing the stations into several groups and conducting inversions with records in each group separately. The number of stations in each group is initially set to be 12, which is regarded as the minimum number for finite-fault inversion (Asano & Iwata, 2009; Saraò et al., 1998). Since the 12 stations may distribute unevenly around the epicenter, we find their partner stations that have similar takeoff angles but nearly opposite azimuths. For each station, we define a two-dimensional Gaussian distribution function with the takeoff angle θ and azimuth φ ,

$$f(x, y) = \frac{1}{2\pi\sigma_\theta\sigma_\varphi} \exp \left[-\frac{1}{2} \left(\frac{(x - \theta)^2}{\sigma_\theta^2} + \frac{(y - \varphi - 180)^2}{\sigma_\varphi^2} \right) \right], \quad (1)$$

where σ_θ and σ_φ are standard deviations in takeoff angle and azimuth, respectively. By calculating the probabilities of all stations, we can get their partner stations that have the highest probabilities. After this pairing, the number of stations in each group is between 12 and 24 because some stations may have the identical partner. The advantage of this strategy is that the stations in each group have a good coverage over the source, and the problematic stations are likely to disperse into different groups so that their effects on the inversion result can be distinguished relatively easily.

By performing inversions for each group, we can get the rupture models and the waveform fittings. If the magnitude is within a reasonable range (e.g., $|M_W - M_{IDS} - M_{inp}| \leq 1$, where $M_W - M_{IDS}$ is the magnitude determined by the IDS method and M_{inp} is the input magnitude from the rapid report such as moment tensor [MT] solution), it can be inferred that good stations are dominant during the inversion, and therefore, stations with poor fittings (average misfit > 0.6) are removed and we will rerun the inversion with the remaining stations. Otherwise, if the magnitude is outside the reasonable range, it would mean that problematic stations may have dominated the inversion result. When this happens, we remove stations with higher fitting values (misfit ≤ 0.6) and rerun the inversion with the remaining stations. We repeat this process until all the problematic stations are removed. Finally, we collect all the remaining stations of all groups and conduct a final inversion.

In general, no prior knowledge on the fault dimension and rupture direction is available immediately after the occurrence of an earthquake. Thus, a sufficiently large fault plane should be assumed. For automatic purpose, we apply the empirical relationships summarized in Wells and Coppersmith (1994) to estimate the dimension of the fault plane and use it as an initial input into the inversion system. After performing one inversion, the automatic system would judge whether the initially assumed fault plane is suitable for slip distribution. If yes, the inversion is terminated, otherwise, the fault size is revised automatically until all slip areas are completely distributed on the fault. We present a simplified flowchart of the automatic inversion system in Figure 2. For this flowchart, the automatic adjustment of the fault sizes involves the following two steps: (1) Review the slip values on all subfaults, and set the slips below 20% of the peak slip to zero. A judgment is then made on whether there exist slips around the fault edges. (2) Expand the fault if slips around the edges are significant, or narrow the fault if slips are far away from the edges. We adopt a linear relationship in extending the side with nonzero slips (Step 2 in Figure 2). The number of rows/columns to be expanded is estimated by the formula, $N = \text{INT}(D/|D - D'|) + 1$, where D the maximum slip on the fault edge and D' that in the neighboring interior row/column. For fault edges no slips are around, we narrow

Figure 2. Flowchart of the automatic finite-fault inversion system in application to the earthquake ($M_w 7.7$) occurred at 15:15 on 11 March 2011 JST.

the fault by keeping two rows/columns with no moment released. The scenario in Figure 2 shows that there are nonzero slips around the top and bottom edges, and no slips around the left edge, indicating that the fault should be wider and shorter. More other scenarios are also provided in supporting information Figures S1–S3. For each event, both nodal planes from the mechanism solution are considered.

To reduce the computation time for synthetic seismograms during the rapid inversion, we established Green's function database in advance, using the all-in-one code QSSP developed by Wang et al. (2017). For simplicity, we use only two velocity models for onshore and offshore earthquakes, respectively. The two velocity models are based on the CRUST1.0 model (Laske et al., 2013) for the crust and a common AK135 global reference model (Kennett et al., 1995) for the lower structure, as shown in Table S1. In the database of Green's functions, the maximum epicentral distance is 1,500 km, and the distance interval linearly increases from 1 km around the epicenter to 5 km at 1,500 km. The maximum depth and the depth interval are 99 and 2 km, respectively.

To check the performance of the automatic inversion system, we conducted two synthetic tests based on the fault model and strong-motion network of the 11 March 2011 $M_w 7.7$ earthquake (#11). A rectangular slip patch, on which the rupture propagates with a constant velocity of 3 km/s, and each subfault ruptures with a single triangular source time function of 16 s duration, is assumed to generate the synthetic waveforms (Figure 3a). In the first test shown in Figure 3b, a 10% Gaussian noise is added into the synthetic data. And in the second test, a slightly different velocity model is used to calculate Green's functions (Figure 3c). The initial fault model built with the empirical relations is too small to capture the real slip distribution. It makes the moment confined in a limited fault area and thus leads to overestimated peak slip. After expanding the fault, the moment magnitude, slip distribution, and the subfault STF are well estimated, although the stations are on the west side of the fault.

Figure 3. Synthetic tests for the 11 March 2011 M_w 7.7 earthquake (Event #11). (a) The left panel shows network stations (triangles) and surface projection of the input slip model. The star is the epicenter, and the beach ball denotes the double-couple mechanism solution. The right panel shows the input subfault STFs and the slip model. (b) Inversion results for the first test in which we invert noisy synthetic data with the correct crustal velocity model. (c) Same as (b), but the crustal models used in generating synthetics (solid ones) and inversions (dashed ones) are different.

3. Results and Comparisons With Other Models

We use the basic source parameters (hypocentral locations and focal mechanism solutions) published on JMA website and the strong-motion records of the 34 significant earthquakes in performing finite-fault inversions following the flowchart in Figure 2 of automatic system. Since both conjugate nodal planes were considered for each event, we obtained a total of 68 rupture models. Each model includes the moment magnitude of an event as well as its source time function, slip distribution, rupture directivity, and velocity. The CPU time spent in the inversion of one earthquake is on average ~ 1.5 min on a desktop PC (CPU Intel i5-6400). All results from the automatic inversions are summarized in a catalog listed in Table S2.

Figure 4. Plots of (a) $M_W - IDS$ versus $M_W - JMA$, (b) $M_W - IDS$ versus $M_W - USGS$, and (c) $M_W - IDS$ versus $M_W - gCMT$. Red and blue circles correspond to magnitudes obtained from the Nodal Planes 1 and 2, respectively. The black solid lines show the straight line with a slope of 1, whereas the dashed and dot-dashed lines represent magnitude differences of 0.1 and 0.2 units from the solid lines, respectively.

Figure S4 presents the complete gallery for the results including distribution of final static slip, snapshots of rupture process, temporal evolution of the accumulative slip, subfault source time functions, as well as comparisons between the observed and synthetic seismograms for each event. Notably, the upper edges of the faults in the slip models are not always the ground surface because the hypocentral depths of some of the earthquakes are quite large, and their ruptures did not reach the surface.

3.1. Fault-Slip Distribution

Among the 34 events, 22 were also analyzed by researchers in Japan, and the results were posted on JMA's official website (<http://www.data.jma.go.jp/svd/eqev/data/sourceprocess/index.html>; last accessed: 17 July 2020). The JMA results were derived from either strong-motion records (16 events) or teleseismic waveform data (6 events). Figure S5 compares the finite-fault models obtained from our automatic inversions in this study with the JMA results. Comparison of the models derived from strong-motion data by the two groups (Figure S5a) shows that the fault dimensions in the automatic inversions are sometimes slightly larger than those in the JMA results, but the major rupture characteristics and rupture extents are extremely consistent, even though there are differences in focal mechanisms and fault geometries (single or multiple faults) for some events. In contrast, the strong-motion models from this study display differences from teleseismic models from JMA results in spatial slip distributions (Figure S5b). Two reasons may account for the differences. One is that the teleseismic data tend to constrain the rupture distribution relative to the initial rupture point (i.e., hypocentral location) because the teleseismic subfault Green's functions are different in time only and similar in waveform. Meanwhile, the near-field strong-motion data can resolve the absolute rupture distribution because the corresponding subfault Green's functions differ in both time and waveform. The second reason is that those events are far away from the strong-motion stations and have relatively large azimuthal gaps in station coverage. In all cases, the rupture extents in the two sets of results are quite similar, suggesting that our models obtained from the automatic inversion system are comparable with those estimated by conventional manual inversion approaches.

3.2. Moment Magnitude and Source Time Function

In Figure 4, we compare the moment magnitudes obtained by our automatic inversions ($M_W - IDS$) with those published by JMA ($M_W - JMA$), the U.S. Geological Survey (USGS, $M_W - USGS$), and the Global Centroid Moment Tensor (gCMT) project ($M_W - gCMT$). Two of the events (M_W 6.3 occurred at 05:07 on 11 August 2009 JST and M_W 7.4 occurred at 15:08 on 11 March 2011 JST) are missing in the gCMT catalog, and one (M_W 7.4 occurred at 15:08 on 11 March 2011 JST) is also missing in the USGS catalog. For each event, magnitudes obtained for the two nodal planes from the automatic system are used in the comparisons, even though the two nodal planes yield nearly identical magnitudes. Overall, our moment magnitudes are very

Figure 5. Comparisons of the normalized source time functions (nSTFs) among different groups. Black lines denote the nSTFs determined in this study, whereas red, blue, and green lines represent the nSTFs released by JMA, USGS, and gCMT, respectively. For each event, the magnitude and the scale factor (SF) for plotting are shown in the top-right corner. The circled numbers correspond to the earthquake numbers listed in Table 1.

close to the other three results with an average difference of 0.07 units. All of the magnitude differences are less than 0.2 units with 85% of them less than 0.1 units. In addition, the three histograms in Figure 4 consistently show Gaussian distributions around zero, indicating that there is no systematic difference between our magnitudes and other results.

Figure 5 shows the normalized source time functions (nSTFs) obtained in this study with those from JMA, USGS, and gCMT solutions. The USGS and gCMT results are obtained from relatively low-frequency teleseismic signals, and both use triangle functions for STFs with relatively low temporal resolution. In comparing the STFs, we do not discuss the details of the STFs of the USGS and gCMT solutions; instead, we mainly focus on the timings of the peaks in the moment-rate functions. All of the STFs were aligned at the origin time of JMA. The results from different groups are mainly consistent with each other. Some STFs from our results have some time delays compared with the JMA results but are more consistent with the USGS and gCMT solutions. For Events #21, #22, and #24 in Figure 5, JMA only released the teleseismic models, and our automatic results have large differences from the other three results. We suspect that this may be due to poor quality of the strong-motion data, which result in unreliable strong-motion results. Here, we define a scaling factor (SF), $SF = \Delta_{min}/R_{rup}$, where Δ_{min} is the minimum source-to-site distance and R_{rup} is the fault length. According to the results shown in Figure 5, inversion results with $SF > 4$ commonly have larger differences compared with other results and may be less reliable, which confirms that the shortest source-to-site distance should not exceed 4 times of the rupture dimension. Notably, Event #10 in Figure 5 (M_w 7.4 at 15:08 on 11 March 2011 JST) shows an acceptable SF value, but the automatic model is distinctly different from JMA model. Since there is no solution for this event in the USGS and gCMT catalogs, the comparison between the automatic and JMA models for this event (#10) is inconclusive. A similar

Figure 6. Comparison of rupture directions between the automatic (black and gray arrows) and JMA (red arrows) rupture models. The JMA models are mostly estimated from strong-motion data except for 6 obtained using teleseismic records shown in panels with gray background. The arrows denote the rupture dimensions and directions from the hypocenters to the moment centroid locations. The beach balls show the focal mechanisms of each event. The circled numbers on the top left of each subpanel are the earthquake numbers listed in Table 1.

difference can also be seen between the automatic and JMA models for Event #11 (M_w 7.7 at 15:25 on 11 March 2011 JST), but our automatic model is fairly consistent with the USGS solution.

3.3. Rupture Direction

We also compare the rupture directions (from the hypocenter to the moment centroid) between the automatic and JMA results. To quantitatively describe the difference, we define an angle φ between the rupture directions of the automatic and JMA models for the same conjugate plane (black and red arrows). As shown in Figure 6, for events whose models are both obtained from strong-motion records, the direction differences are very small ($\varphi < 10^\circ$ for most events), except for Events #28 (M_w 6.8 at 06:12 on 13 May 2015 JST) and #31 (M_w 6.0 at 00:03 on 15 April 2016 JST). For Event #28, NIED also released a model suggesting a major north-westward rupture propagation (NIED, 2017), which is more consistent with our automatic model. For Event #31, Kobayashi et al. (2017) derived a model by performing a joint inversion of strong-motion, teleseismic and geodetic data, which showed that the rupture mainly propagated southeastward, which is also closer to our model. However, there are relatively large angular differences in rupture directions between the automatic strong-motion and JMA teleseismic models. The reasons could be the same as discussed for Figures 5 and S5b; that is, teleseismic data tend to constrain the ruptures relative to the hypocentral location and that the strong-motion stations are located far away from the sources (large SF). Furthermore, we also plot the rupture directions of the automatic strong-motion model based on the conjugate nodal planes (gray arrows in Figure 6). The rupture models based on the conjugate nodal planes show significantly different rupture directions. This implies that identifying the actual fault plane is critical to effectively determine the rupture direction and meizoseismal areas.

3.4. Rupture Speed

For each event, we calculate the rupture speed based on the two automatic models for the conjugate nodal planes. Because the subfault source time functions have complex shapes, identifying the rupture initiation

Figure 7. The moment-weighted average rupture speeds from the automatic finite-fault inversions of the 34 earthquakes for $\xi = 0.1, 0.2$, and 0.3 . Red and blue diamonds correspond to speeds obtained from Nodal Planes 1 and 2, respectively. For each event, the error bar is the weighted standard deviation σ_v (the symbol corresponds to the average value). The beach balls on the top are JMA solutions with colors in magenta, cyan, and purple for thrust, strike-slip, and normal events, respectively.

time is dependent on the threshold of moment rate. We in turn calculate the moment-weighted average rupture speed ($\bar{v}$), given by

$$\bar{v} = \sum_{t=1}^T [v(t)\Delta M(t)]/M_0, \quad (2)$$

where $M_0 = \sum_{t=1}^T \Delta M(t)$ is the scalar seismic moment, and $v(t)$ and $\Delta M(t)$ are the moving speed of the centroid and the rate of moment release at time t , respectively. The uncertainty (standard deviation) of the rupture speed is defined as

$$\sigma_v = \sqrt{\sum_{t=1}^T \Delta M(t)[v(t) - \bar{v}]^2 / [(T - 1)M_0]}. \quad (3)$$

In each time instant, we set a threshold (ξ) and ignore any moment rates smaller than ξ times the peak moment rate. Different threshold values were considered from 0.1 to 0.3 with an interval $\Delta\xi = 0.1$. Figure 7 shows the rupture speeds and their uncertainties for the 34 earthquakes. The rupture speeds remain almost unchanged with increased threshold (ξ). The uncertainties of rupture speeds are sometimes large, suggesting significant variations of the rupture speed during the earthquake rupture processes. In addition, large uncertainties of rupture speed are also found for small earthquakes especially for some normal-fault events near the trench (Figure 1). One reason maybe that the source-to-site distances are significantly larger than the source dimensions, and thus, the inversions constrain the rupture behaviors relatively poorly.

Figure 8. Comparisons of centroid drift speeds (v_c) between the automatic (red diamonds) and JMA (green squares) rupture models. The beach balls on the top are JMA moment tensor solutions, with colors in magenta, cyan, and purple for thrust, strike-slip, and normal events, respectively.

Among the 34 earthquakes, there are 26 events (marked by red numbers in Figure 7) for which JMA has identified the actual fault planes in its released rupture models (JMA, <http://www.data.jma.go.jp/svd/eqev/data/sourceprocess/index.html>; last accessed: 19 July 2020; Fujii & Satake, 2008; Nagoya University, 2008). For most of these 26 events (nearly 70%) the average rupture speeds based on the JMA's fault planes (Nodal Plane 1) are larger than those on the conjugated planes. This may be because that the rupture extensions were restricted around the hypocenter in inversions using the conjugate planes and thus resulted in lower rupture speeds or weakly defined rupture directivities. Therefore, the difference in rupture speeds between the two conjugate nodal planes may provide an additional qualitative criterion in the quick identification of the actual fault plane.

In addition, we obtain the average centroid drift speeds for the 26 events estimated by $v_c = \frac{L_c}{T_c}$, where L_c is the distance from the hypocenter to the moment centroid position and T_c the centroid time delay given by $T_c = \frac{\int_0^T tM(t)dt}{M_0}$. We compare the centroid drift speeds obtained from the automatic and JMA rupture models (Figure 8). The comparison shows that the centroid drift speeds (v_c) from the two groups are fairly consistent with each other, indicating the reliability of the rupture models inverted by the automatic method.

We also obtain the relationship between the rupture areas (A) and the scalar seismic moment (M_0) (Figure S6). Most of the static stress drops are between 1 and 10 MPa, consistent with the results given by other researchers (Aki, 1972; Ammon et al., 2011; Asano & Iwata, 2016; Chinnery, 1964; Fujii et al., 2011; Gusman et al., 2012; Hayes, 2011; Ide et al., 2011; Kanamori & Anderson, 1975; Kubo et al., 2016; Lay et al., 2011; Satake et al., 2013; Shao et al., 2011; Wei et al., 2012; Yagi et al., 2016; Yagi & Fukahata, 2011b; Yamazaki et al., 2011; Yue & Lay, 2013).

4. Discussion

4.1. Earthquake Magnitude Estimation

The automatic inversion system is an iterative process in which the inversion can be performed several times to update the dimension of the fault plane. However, the initial fault plane based on the empirical scaling relation can still provide well-estimated magnitudes. Figure 9 compares the moment magnitudes determined from the initial ($M_{W-initial}$) and final fault models ($M_{W-final}$). The two magnitudes are almost identical. The average magnitude difference is only about 0.03 units, and 99% of the differences are less than 0.1 units. We also plot the source time functions estimated based on the initial and final fault models in Figure S7. The moment-rate functions are extremely similar. Moreover, the two nodal planes for each event produce nearly identical magnitudes and source time functions. This suggests that magnitude and source time function estimations are more or less independent of the orientation and size of the fault plane. Given that MT inversion uses far-field data to satisfy the point-source approximation, there may be no MT solutions available immediately after the earthquake. In this case, we can perform finite-fault inversion

Figure 9. Comparisons between the moment magnitudes estimated with the initial and final fault models. Red and blue dots are magnitudes obtained using Nodal Planes 1 and 2, respectively. The black solid line is the straight line with a slope of 1, whereas the dashed and dot-dashed lines represent magnitude differences of 0.1 and 0.2 units from the solid line, respectively. The histogram shows the distribution of the difference between the initial and final magnitudes.

with the near-field data based on the known geological settings/active faults/historical mechanisms and obtain moment magnitude and STF. This practice may provide more timely results for earthquake emergence responses.

4.2. Resolving Fault Plane Ambiguity by Finite-Fault Inversion

Whether the misfits of finite-fault inversions based on the two nodal planes can distinguish the actual rupture plane is a topic of debate in earthquake source studies. To investigate this issue, we performed finite-fault inversions with different cutoff frequencies using the 26 events whose actual fault planes have been identified by JMA. Focal mechanisms from the USGS and gCMT catalogs for these events are also considered. We conduct finite-fault inversions for each event using strong-motion records with increasing upper cutoff frequencies from 0.1 to 0.4 Hz with an increment of 0.1 Hz. Note that the misfits of both nodal planes for each event are calculated at the same stations, which are screened using the actual fault plane. Figure 10 shows the differences in misfits between the finite-fault inversions based on the two conjugate planes of each event. Most of the misfit differences are negative, suggesting that the actual fault planes (identified by JMA) indeed yield better waveform fits. However, some of the misfit differences are small, which may lead to difficulty in fault plane identification. The reason for the small misfit differences could be that the available station coverage has larger azimuthal gaps or greater distances from the source, which degrades the resolution on the finite-source ruptures, especially when the magnitude is small. This demonstrates that resolving the fault plane ambiguity problem requires a good station distribution, particularly for events of moderate strength.

Figure 10 shows that several onshore events with good station coverage also have small misfit differences. This is probably due to the fact that we used the same structural model for all the onshore events without considering the effect of lateral heterogeneities.

In the five normal-fault events (purple beach balls) shown in Figure 10, four of them show that the fault planes identified by JMA yield even larger misfits than the conjugate planes. Two of them (#17 M_W 6.7 at 17:16 on 11 April 2011 JST and #23 M_W 7.3 at 17:18 on 12 July 2012 JST) are believed to involve ruptures on multiple faults (Figure S5). Compared with normal-fault events, it is relatively easy to identify the rupture fault planes for strike-slip events with multiple faults (Kuge, 2003), such as Events #5 (M_W 6.3 at 05:07 on 11 August 2009 JST) and #32 (M_W 7.0 at 01:25 on 16 April 2016 JST). Normal-fault Events #22 (M_W 6.9 at 18:08 on 14 March 2012 JST) and #24 (M_W 7.1 at 02:10 on 26 October 2013 JST) occurred far away east of the Japan Trench (Figure 1) and have relatively large distances from the stations (more than 310 km), which may have led to difficulties in identifying its actual fault plane. Therefore, normal-fault events may require more efforts to determine their actual fault planes.

In summary, comparisons in Figure 10 suggest that the misfits can provide important information in the identification of the actual fault planes. However, it may not be always robust, especially for normal-fault events. Additional information is necessary for rapid identification of the fault planes to improve the reliability of earthquake emergency responses and tsunami warnings. An alternative way is that when the causative fault is not well distinguished, we can use the rupture models obtained from the two conjugate nodal planes to synthesize the strong ground motion and tsunami heights and make decisions based on the one with more serious damage.

4.3. Comparison of Inversions Between Borehole KiK-net and K-NET Data

In this study, we used the KiK-net data in inversions of all 34 significant earthquakes. The high-quality borehole data are ideal for source inversion. In many other areas, however, many strong-motion stations are deployed on the ground surface. To check the applicability of the automatic inversion in more general cases, we conducted inversions with the K-NET data and compared the results with those of borehole KiK-net

Figure 10. Misfit differences of inversions with both nodal planes from the mechanism solutions of JMA, USGS, and gCMT catalogs. Misfit difference here is defined as the misfit of the actual rupture plane minus that of the conjugate plane. The beach balls on the top are the same ones as illustrated in Figure 8. Circles with different colors correspond to different upper cutoff frequencies.

inversions. Three earthquakes, including an inland strike-slip event (#14, M_W 6.0), a nearshore thrust event (#7, M_W 6.5), and an offshore normal-faulting event (#12, M_W 7.5), were analyzed by inverting the K-NET data. The data processing and Green's function calculation were the same as the KiK-net inversions introduced earlier.

The results of KiK-net and K-NET inversions are shown in Figure S8. Although the final fault sizes are slightly different, the moment magnitudes, STFs, and detailed slip distributions are extremely similar to each other. In general, the misfits of K-NET inversions are larger than borehole KiK-net, except for the inversion of Event #14 in which much fewer stations from the K-NET were used. The similarities between the inversion results of the two networks indicate that the automatic inversion system can work equally well for surface-deployed strong-motion networks.

4.4. Future Improvements to the Automatic Finite-Fault Inversion System

Several preconditions must be met before our automatic finite-fault inversion system can be effective for emergency response and tsunami early warning applications: (1) Real-time seismic waveform data are available; (2) hypocenter location and focal mechanism can be determined in real time; and (3) local earth structure is known so that a database of Green's functions can be established. Current EEW systems can meet all these prerequisites except for the focal mechanism. In this study, the focal mechanisms are taken from results released by JMA, USGS, and gCMT, which at present may take a few minutes to several hours. Fortunately, most large earthquakes occur on the existing active faults with known focal mechanisms. For great subduction zone earthquakes, for example, the fault geometry can be assumed based on the global subduction zone model USGS Slab2.0 (Hayes et al., 2018). There is no need to wait for the inversion of focal mechanism in order to save time in an emergency. However, there are still certain earthquakes occurring

on known faults but with unexpected mechanisms or even on unmapped faults, such as the 2010 M_W 7.0 Haiti earthquake (Calais et al., 2010), the 2013 M_W 8.6 Sumatra earthquake (Yue et al., 2012), and the 2019 M_W 7.0 Ridgecrest earthquake (Ross et al., 2019). Therefore, for EEW purpose, regional tectonics in earthquake-prone areas should be investigated in advance, and techniques for real-time determination of focal mechanism also need to be developed. In fact, methods for real-time inversion of focal mechanisms have been developed. Tsuruoka, Kawakatsu, and Urabe (2009) developed a grid-based MT inversion (GRiD MT) system, which determines the MT solutions every second using long-period data recorded by the F-net. However, the system is not suitable for earthquake larger than M_W 6.5. To increase the range of magnitude monitoring, Tsuruoka, Rivera, et al. (2009) implemented the W-phase MT algorithm (Kanamori & Rivera, 2008) into the GRiD MT system using regional and global broadband seismic records. The updated system can determine the MT solutions within 6 min for regional earthquakes and within 15 min for global ones. Melgar et al. (2012) presented method for rapid MT estimation using real-time high-rate GPS displacements. Lee et al. (2014) established an automatic system for real-time determination of MT in Taiwan using broadband records, although broadband data may not be available for large earthquakes due to limited dynamic range. Further development of the real-time or fast MT inversion may need to jointly use seismic and geodetic data to provide a more efficient and robust estimation of the fault parameters. For large earthquakes, the point-source approximation demands that the site-to-source distance should be larger than the source dimension, which means that near-fault data cannot be used, thus lowering the efficiency of the MT inversion. Much efforts should be made in the future to resolve these technical issues in order to establish an automatic system for the determination of complete source parameters, including the earthquake location, focal mechanism, and finite-fault rupture process.

In applying the IDS method, the mechanism needs to be fixed for the deconvolution, and therefore, our automatic inversion cannot resolve the change in rake, although this change can be significant in large earthquakes, for example, the 2008 Wenchuan earthquake (Zhang & Wang, 2015). This may to some extent suppress the slips on subfaults whose rake angles are remarkably different from the average value. Moreover, single-fault plane is considered in our automatic system since there is very little information on the complex faults immediately after an earthquake. This may also lead to the loss of rupture details. Although fixed-mechanism and single-fault model are assumed in the automatic system, the rupture direction and the location of meizoseismal areas can still be reliably estimated (as shown in Figure 6), which are essential for hazard assessment, early warning, and mitigation purposes.

The performance of the automatic finite-fault inversion system also depends on the establishment of Green's function database. So far, we have used two 1-D velocity models to construct the database of Green's functions for earthquakes in and around Japan, which yield sufficiently robust inversion results. Our automatic inversion results and the JMA rupture models share consistent major rupture behaviors for most cases, demonstrating that single 1-D velocity model can be used in rapid response and tsunami early warning operations. In future improvements of the automatic system, it is feasible to consider 3-D velocity models in the calculation and preparation of Green's function database (Hejrani et al., 2017; Hsieh et al., 2016). This demands a realistic 3-D model, which effectively removes the 3-D structural influence on the waveforms (Liu & Archuleta, 2004).

It takes about 1.5 min for each inversion on a typical desktop PC, with strong-motion records available and earthquake location and focal mechanism already determined. It should be noted that most of the CPU time is spent on station grouping screening to distinguish the problematic and effective stations (see the supporting information). Moreover, the deconvolution and stacking procedures of IDS algorithm are computed independently from subfault to subfault, implying that it can be easily parallelized. If the procedure is implemented on a supercomputer, the computation time can be negligible. In the future, with the continuous improvements in station coverage and data quality, it can be expected that the station selection can be done more efficiently and the automatic inversion can be completed within several to tens of seconds.

So far we have used only the strong-motion records in the automatic inversion system. In principle, other near-field data sets, such as the high-rate GPS records (e.g., Zhang et al., 2014), unclipped broadband waveforms, and the geodetic deformation data, can be used for the purpose of emergency responses. Currently, teleseismic data recorded by the Global Seismographic Network (GSN) are commonly used in finite-fault inversions of global earthquakes (e.g., Koch et al., 2019). The teleseismic data can be easily obtained, but

the response time is much longer than local recordings. To speed up the emergency responses, we can use strong-motion data and geodetic deformation and/or waveform data recorded at near-field distances. Compared with geodetic measurements, strong-motion stations are usually deployed at soft-soil sites. This may lead to baseline shifts at low frequencies and amplifications at high frequencies. In this case, band-pass filters are needed for strong-motion data in the inversions of source parameters. On the other hand, the low-to-zero frequencies are important to estimate the magnitudes and fault sizes of large earthquakes. Although the baseline shifts have been able to be corrected so that the signals at low-to-zero frequencies can be well recovered, the corrections are not easy to achieve in real-time processing (e.g., Wang et al., 2011). Band-pass filter is a convenient way for strong-motion inversion for both postearthquake and real-time analyses. The cost, however, is the underestimates of earthquake scale and fault size. Zhang et al. (2014) have inverted both high-rate GPS and strong-motion data of the 2011 Tohoku earthquake and found that the former resulted in a larger magnitude (M_W 9.05 vs. M_W 9.03) and a higher peak slip (60 vs. 51 m). The advantage of strong-motion data, however, is that they are the most common and easily obtainable data at near-field distances. Besides NIED, which routinely releases the strong-motion data of earthquakes around Japan, the Center for Engineering Strong Motion Data (CESMD) and the Pacific Earthquake Engineering Research Center (PEER) Strong Motion Databases routinely collect and release the strong-motion data after occurrences of many global/regional significant earthquakes. The European Strong-Motion Database (ESD) also provides strong-motion records for significant earthquakes in Europe. There are many more strong-motion databases that provide localized data services, such as the USGS National Strong-Motion Project (NSMP, the United States), the Canadian National Seismograph Network (CNSN, Canada), the GeoNet Strong-Motion Data (New Zealand), the Iran Strong Motion Network (ISMN, Iran), and others established by individual countries in Europe (e.g., France, Italy, Greece, and Turkey; see Table S3). In addition, the China Earthquake Administration (CEA) is deploying the largest strong-motion network in the world, which contains >5,000 conventional strong-motion seismographs and >10,000 microelectromechanical system (MEM) accelerometers. This large-scale strong-motion network ensures dense coverage in most seismically active areas in China (interstation spacing ~20 km). All recordings will be transmitted in real time to provide a timely alert for strong shakings in the Chinese mainland. Abundant strong-motion data present an optimistic future outlook for real-time automatic inversions of earthquake finite-fault rupture models.

5. Conclusions

We have developed an automatic system to rapidly estimate the finite-fault rupture models. The effectiveness of the system has been demonstrated by the inversions of strong-motion seismograms of significant earthquakes in and around Japan. With this inversion system, we can automatically and reliably estimate the rupture model in a very short time (~1.5 min). The rupture models determined in real time can provide valuable information for both emergency response and tsunami early warning. Moreover, our methodology can be used to construct a completely automatic system for the determination of source parameters. With the development of seismic networks, it will become feasible for earthquake monitoring agencies around the world to quickly and routinely determine and release rupture models, just as what the current EEW systems are doing in determining hypocentral locations and MT solutions. In regions with good network coverage, we can also establish catalogs of finite-fault rupture models for past earthquakes using the inversion system developed in this study, which can be used in both theoretical studies of earthquake physics and practical applications in disaster reduction purposes.

Data Availability Statement

The strong-motion data are downloaded from the website of the National Research Institute for Earth Science and Disaster Resilience (NIED, https://www.kyoshin.bosai.go.jp/kyoshin/search/index_en.html). The moment tensor solutions involved in this work are released by the Japan Meteorological Agency (JMA, <http://www.data.jma.go.jp/svd/eqev/data/bulletin/eqdoc.html#table 6>), the U.S. Geological Survey (USGS, <https://earthquake.usgs.gov/earthquakes/search/>), and the Global Centroid Moment Tensor (gCMT) group (<https://www.globalcmt.org/CMTsearch.html>). The source rupture models for comparison with our automatic models are from NIED (<https://www.kyoshin.bosai.go.jp/kyoshin/inversion/>).

inversion_main_en.shtml), JMA (<http://www.data.jma.go.jp/svd/eqev/data/sourceprocess/index.html>), and SRCMOD database (<http://equake-rc.info/srcmod/>).

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