Terr. Atmos. Ocean. Sci., Vol. 21, No. 4, 645-654, August 2010

doi: 10.3319/TAO.2009.08.25.01(T)

Source Parameters of the 2005 M_w 7.2 Miyagi-Oki, Japan, Earthquake as Inferred from Teleseismic *P*-Waves

Ruey-Der Hwang[1, *], Tzu-Wei Lin[2], Guey-Kuen Yu[3, 4], Jo-Pan Chang[1], and Wen-Yen Chang[5]

[1] Department of Geology, Chinese Culture University, Taipei 111, Taiwan, ROC
[2] Seismology Center, Central Weather Bureau, Taipei 100, Taiwan, ROC
[3] Department of Civil Engineering, Vanung University, Jhongli 320, Taiwan, ROC
[4] Institute of Geophysics, National Central University, Jhongli 320, Taiwan, ROC
[5] Department of Natural Sciences, National Science Council, Taipei 106, Taiwan, ROC

Received 5 December 2008, accepted 25 August 2009

ABSTRACT

We investigate the fault parameters of the 2005 Miyagi-Oki (Japan) earthquake using duration variations of teleseismic *P*-waves. The results show that the earthquake has a thrust-type mechanism and a seismic moment of 4.46×10^{19} Nm. Rupture directivity analysis suggests that the earthquake occurred as a result of a bilateral faulting on the fault plane with a strike of 247°, a dip of 17° and a slip of 125°. The optimal rupture azimuth, measured counterclockwise from the strike on the fault plane, is 170° (or 350°). The rupture length and average source duration are estimated to be 73.4 km and 14.5 sec, respectively. Thus the rupture velocity is 2.53 km sec^{-1} (~0.57 times the value of *S*-wave velocity), which is lower than the value for other similarly sized earthquakes. This implies that the 2005 Miyagi-Oki earthquake was probably a slow event. Consequently, there may have been less release of high-frequency seismic energy, leading to lower radiated seismic energy and radiation efficiency (~0.32 - 0.48). In other words, relatively larger fracture energy occurred during earthquake faulting in addition to the heat due to friction. The ratio of the static stress drop to the apparent stress (> 2.0) also suggests that the earthquake can be modeled as a frictional overshoot in a stress model, which implies the transformation of a lower percentage of strain energy into seismic-wave energy during the process of earthquake rupturing.

Key words: Source duration, Rupture directivity, Bilateral faulting, Radiated seismic energy, Radiation efficiency, Fracture energy

Citation: Hwang, R. D., T. W. Lin, G. K. Yu, J. P. Chang, and W. Y. Chang, 2010: Source parameters of the 2005 M_w 7.2 Miyagi-Oki, Japan, earthquake as inferred from teleseismic P-waves. Terr. Atmos. Ocean. Sci., 21, 645-654, doi: 10.3319/TAO.2009.08.25.01(T)

1. INTRODUCTION

Fault parameters and rupture directivity for earthquakes provide important information for understanding the physical behavior of earthquake ruptures (Ben-Menahem 1961; Kanamori and Heaton 2000). Generally, the focal mechanism is determined using moment tensors inversion (e.g., Dziewonski et al. 1981; Sipkin 1994); the estimation of the rupture directivity of an earthquake is primarily based on variation of the source duration with a station azimuth and source finiteness theory (cf. Ben-Menahem 1961; Chung and Kanamori 1980). Several methods are employed to derive source-duration variations with an azimuth, for example, using empirical Green's function and forward waveform modeling (e.g., Kanamori and Stewart 1976; Chung and Kanamori 1980; Ruff and Kanamori 1983; Ammon et al. 1993). Macroscopic source parameters (including radiated seismic energy, fracture energy and rupture velocity, etc.) are also helpful to understand earthquake rupture mechanisms (Kanamori 1994; Kanamori and Heaton 2000; Venkataraman and Kanamori 2004). Radiated seismic energy can be determined either from teleseismic *P*-waveforms or from a source time function (e.g., Vassiliou and Kanamori 1982; Kikuchi and Fukao 1988; Choy and Boatwright 1995; Pérea-Campos and Beroza 2001; Bilek et al. 2004; Venkataraman and Kanamori 2004). In general, the ratio (E_s/M_o) of radiated seismic energy (E_s) to seismic moment (M_o) is related to the dynamics of earthquake faulting; hence E_s/M_o can be employed to obtain some indication of the condi-

* *Corresponding author*
E-mail: hrd@faculty.pccu.edu.tw

tion of stress during an earthquake (Wyss and Brune 1968; Kanamori and Heaton 2000; Hwang et al. 2001; Kanamori and Rivera 2004). A large E_s/M_o indicates a rapid drop in friction during earthquake faulting, while a relatively low E_s/M_o indicates that friction drops more slowly (Kanamori and Heaton 2000). However, there is high divergence in the E_s/M_o derived in previous studies because of uncertainty in the estimated radiated seismic energy. For example, Kikuchi and Fukao (1988) estimated the E_s/M_o for large earthquakes to be 5.0×10^{-6}; Choy and Boatwright (1995) found a global average E_s/M_o of 1.6×10^{-5}; Vassiliou and Kanamori (1982) and Kanamori and Heaton (2000) found the E_s/M_o for large earthquakes to be 5.0×10^{-5}; Pérea-Campos and Beroza (2001) obtained an E_s/M_o value of 4.7×10^{-6} for reverse faulting earthquakes; Bilek et al. (2004) found a relatively lower E_s/M_o of 5.6×10^{-6}; while Hwang et al. (2001) estimated a relatively larger E_s/M_o of $1.0 - 3.0 \times 10^{-4}$ for the 1999 Chi-Chi earthquake from near-field seismograms. Moreover, usage of a finite frequency bandwidth usually leads to underestimation of radiated seismic energy (Boore 1986; Di Bona and Rovelli 1988; Ide and Beroza 2001; Wang 2004; Wang and Huang 2007). In spite of the difficulty in estimating radiated seismic energy, it is known that the E_s/M_o of strike-slip earthquakes is significantly different from that of reverse and normal earthquakes, i.e., E_s/M_o is dependent on focal mechanism (e.g., Choy and Boatwright 1995; Pérez-Campos and Beroza 2001). Finally, it should be noted that tsunami earthquakes have a lower E_s/M_o than do other types (Newman and Okal 1998; Bilek et al. 2004). In addition, the relationship between the static stress drop and apparent stress also can indicate the stress mechanism, a partial-stress drop model or a frictional overshoot mechanism (Zúñiga 1993).

On 16 August 2005, a large earthquake ($M_w = 7.2$) occurred offshore near Miyagi Prefecture in northeastern Japan. This earthquake had a focal depth of 36 km as reported by USGS. The epicenter is displayed in Fig. 1. Also shown in Fig. 1 are the station distribution and aftershocks that occurred over the following 2 months. The location of the 2005 Miyagi-Oki earthquake was close to the epicenter of an earthquake, which occurred in 1978 (Okada et al. 2005; Yagi 2005). Earthquakes with $M_w \geq 7.0$ have occurred repeatedly in northeastern Japan, at an interval of approximately 30-year (cf. Yamanaka and Kikuchi 2004). Okada et al. (2005) analyzed the rupture process and suggested that the 2005 Miyagi-Oki earthquake possibly caused rupturing in the source area of the 1978 Miyagi-Oki earthquake. They also found that the coseismic slip distribution more or less followed the dip-direction of the fault. However, Yagi (2005) and the ERI report (EIC Seismological Note: No.168) showed that the coseismic slip was distributed along the strike-direction of the fault. Furthermore, the aftershocks of the 2005 Miyagi-Oki earthquake (see Fig. 1) occurred mainly along the dip-direction of the fault. They mostly surrounded the main area of the rupturing as derived by Yagi (2005). In other words, both Yagi's results and the coseismic slip distributions in the ERI report seem to agree well with the asperity source model (e.g., Ruff and Kanamori 1983). In this study, we attempt to infer the source mechanism and parameters of the Miyagi-Oki earthquake by utilizing the far-field *P*-waveform inversion procedure proposed by Lin et al. (2006). With this inversion process, we can simultaneously derive the fault plane solution, the seismic moment, and the rupture directivity of the earthquake. The estimated fault parameters can then be used to calculate the macroscopic source parameters, which give us a better understanding about the physical behavior of rupture during the 2005 Miyagi-Oki earthquake.

2. METHOD

The method proposed by Lin et al. (2006) is employed in this study. It differs from both the moment tensor inversion method (e.g., Dziewonski et al. 1981; Sipkin 1994) and empirical Green's function (Ammon et al. 1993). Traditionally, for a shallow earthquake, a synthetic far-field seismogram at a particular receiver can be expressed in the following form [for details, see Kanamori and Stewart (1976) and Okal (1992)]:

$$u^P(t) = \frac{M_0}{4\pi\rho_h\alpha_h^3} \cdot \frac{g(\Delta)}{r} \cdot \Bigg[R^P f(t - t_P) + R^{pP} V_{pP} f(t - t_{pP}) + R^{sP} \frac{\alpha_h \cos i_h}{\beta_h \cos j_h} V_{sP} f(t - t_{sP}) \Bigg] \cdot C^P(i_o) * Q(t) * I(t) \quad (1)$$

$u^P(t)$ is the synthetic far-field seismogram; M_o is the seismic moment; α_h, β_h, and ρ_h are the *P*-wave velocity, *S*-wave velocity and density in the source area, respectively; $g(\Delta)$ denotes the geometrical spreading factor as a function of epicentral distance (Δ) and focal depth; r is the radius of the Earth (about 6371 km); R^P, R^{pP}, and R^{sP} are the radiation patterns for the *P*-, *pP*- and *sP*-waves (cf. Kanamori and Stewart 1976; Aki and Richards 1980); V_{pP} and V_{sP} denote the reflection coefficients of the *P*- to *P*-wave and the *S*- to *P*-wave at the free surface (cf. Aki and Richards 1980); i_h and j_h are the take-off angles of the *P*- and *S*-waves just leaving the source and i_o is the incident angle of the *P*-wave in relation to the free surface; $C^P(i_o)$ is the free surface effect at the receiver (cf. Aki and Richards 1980); $f(t)$ stands for a triangular source time function and its duration represents the source-process time; t_P, t_{pP}, and t_{sP} are the travel times for the *P*-, *pP*- and *sP*-waves, which are calculated according to a given Earth velocity model; $Q(t)$ is the attenuation filter of the Earth based on Azimi's law (e.g., Yoshida 1988); $I(t)$ is the instrumental response. Figure 2 shows a sketch of generating a synthetic far-field seismogram, exclusive of the instrumental response.

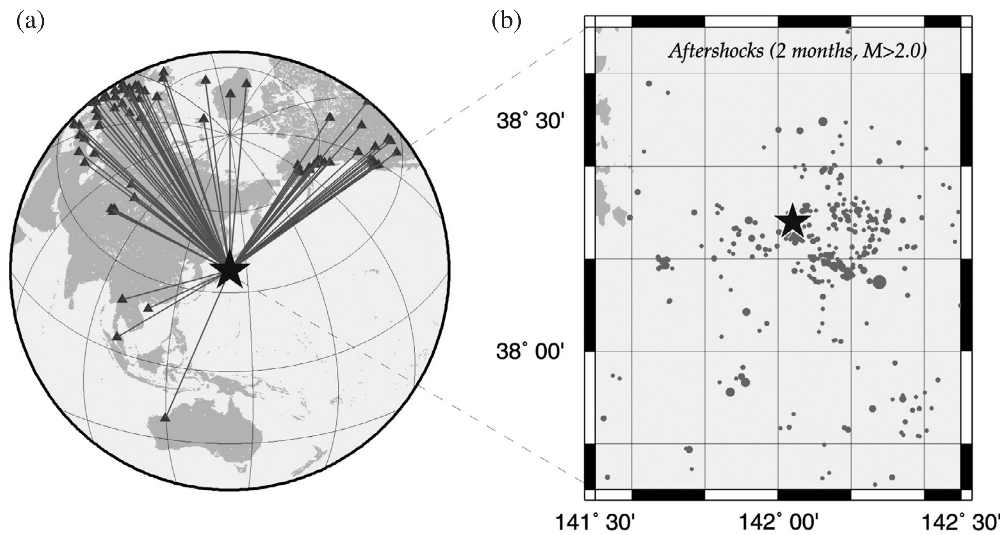

Fig. 1. (a) Distribution of the available stations (triangles) and the epicenter of the 2005 Miyagi-Oki earthquake (star). (b) Map showing the distribution of aftershocks (circles) with $M_w > 2.0$.

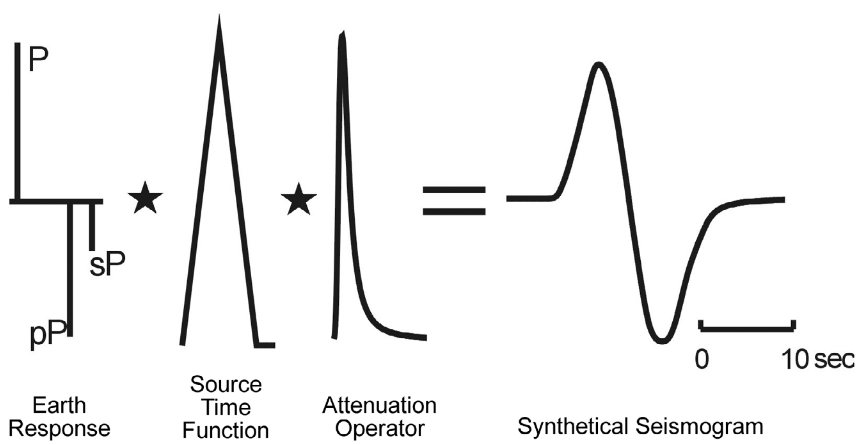

Fig. 2. Schematic diagram representing the generation of a far-field synthetic seismogram. The triangular source time function is used in this study. The earth response is calculated from the *iasp91* velocity model. The star (★) indicates the convolution operator.

After taking into account some corrections to the seismogram, we can rewrite Eq. (1) in the following form:

$$u_c^P(t) = u^P(t)\cdot 4\pi\rho_h\alpha_h^3\cdot\frac{r}{g(\Delta)}\cdot\frac{1}{C^P(i_o)} = \Big[M_oR^Pf(t-t_P) + M_oR^{pP}V_{pP}f(t-t_{pP}) + M_oR^{sP}\frac{\alpha_h\cos i_h}{\beta_h\cos j_h}V_{sP}f(t-t_{sP})\Big]*Q(t) \qquad (2)$$

where $u_c^P(t)$ is the corrected seismogram, not inclusive of the instrumental effect, geometrical spreading, the free surface effect, etc. The unknown parameters in Eq. (2) are M_o, R^P, R^{pP}, and R^{sP}, that is, the seismic moment and radiation patterns. For convenience in solving for the unknown parameters for each station, Eq. (2) can be expressed in matrix form with n data points and 3 unknown parameters (M_oR^P, M_oR^{pP}, M_oR^{sP}) as follows:

$$\begin{bmatrix} Q(t_1)*f(t_1-t_P),\ V_{pP}Q(t_1)*f(t_1-t_{pP}),\ \dfrac{\alpha_h\cos i_h}{\beta_h\cos j_h}V_{sP}Q(t_1)*f(t_1-t_{sP}) \\ Q(t_2)*f(t_2-t_P),\ V_{pP}Q(t_2)*f(t_2-t_{pP}),\ \dfrac{\alpha_h\cos i_h}{\beta_h\cos j_h}V_{sP}Q(t_2)*f(t_2-t_{sP}) \\ \ldots\ldots \\ Q(t_n)*f(t_n-t_P),\ V_{pP}Q(t_n)*f(t_n-t_{pP}),\ \dfrac{\alpha_h\cos i_h}{\beta_h\cos j_h}V_{sP}Q(t_n)*f(t_n-t_{sP}) \end{bmatrix} \begin{bmatrix} M_oR^P \\ M_oR^{pP} \\ M_oR^{sP} \end{bmatrix} = \begin{bmatrix} u_c^P(t_1) \\ u_c^P(t_2) \\ \ldots \\ u_c^P(t_n) \end{bmatrix} \qquad (3)$$

The *iasp91* velocity model (Kennett and Engdahl 1991) is used to calculate the travel time of seismic-waves as well as several parameters. The attenuation filter $Q(t)$ is calculated by Azimi's law and using $t^* = 1.0$ (travel time over quality factor) for the P-wave (cf. Okal 1992). The parameters to be solved in Eq. (3) are M_oR^P, M_oR^{pP}, and M_oR^{sP}, which are the so-called pseudo radiation patterns (Lin et al. 2006). The pseudo radiation pattern is defined as the product of seismic moment (M_o) and radiation pattern (R^P, R^{pP}, R^{sP}). Equation (3) can be solved by the standard least-squares technique (cf. Menke 1984). The inversion process in Eq. (3) has two solutions. One is the source duration; the other is the pseudo radiation pattern. In other words, we find the corresponding pseudo radiation pattern when giving a source time function with a fixed source duration. Thus, we search for a succession of source time functions with various source durations. The appropriate source duration and pseudo radiation patterns are obtained for each station by minimizing misfits between the observed and synthetic seismograms. The fault plane solution and seismic moment are derived afterwards from a grid search of the strike, dip and slip angles of the fault by making a comparison between the theoretical and pseudo radiation patterns at an interval of 1° (also refer to Lin et al. 2006). The rupture feature of the earthquake, i.e., unilateral or bilateral faulting mechanism, can be judged through rupture directivity analysis based on the source duration variations with station azimuth (cf. Ben-Menahem 1961; Chung and Kanamori 1980; Lin et al. 2006). From the viewpoint of the source finiteness theory of Ben-Menahem (1961), the relationship between observed source duration and several fault parameters for an earthquake with unilateral faulting can be expressed as:

$$T = \frac{L}{V_R} - \frac{L}{V_C}\cos\Theta \qquad (4)$$

and for bilateral faulting can be written as:

$$T = \frac{L}{2V_R} + \frac{L}{2V_C}\left|\cos\Theta\right| \qquad (5)$$

where T is the source duration observed at a given station, L is the rupture length, V_R is the rupture velocity, V_C is the P-wave velocity in the source area, and Θ is the angle between the rupture direction and a ray taking off from the source. The rupture direction is measured counterclockwise from the strike of the fault on the fault plane. Through rupture directivity analysis, the fault parameters can be easily estimated by using the aforementioned equation through the least-squares technique.

3. DATA

The IRIS (Incorporated Research Institutions for Seismology) Data Management Center collected hundreds of seismograms which have been recorded by several seismic networks during the 2005 Miyagi-Oki earthquake. This provides a wealth of high-quality seismic data from which to analyze the rupture behavior of the 2005 Miyagi-Oki earthquake. In order to eliminate the interference of depth phases (such as the PcP-wave) and multipathing waves (such as the PP-wave), only seismograms recorded at epicentral distances of 30° - 90° are used. We extract the 50-sec-long P-waves, including the first 5 sec of the P-arrival and the 45 sec after the P-arrival, from the original seismogram. In the inversion, the travel times of the P-, pP-, and sP-waves, geometrical spreading, take-off angle, free surface effect and reflection coefficients are calculated according to the *iasp91* velocity model (Kennett and Engdahl 1991). The P-wave velocity, S-wave velocity and density at the source area of the 2005 Miyagi-Oki earthquake are 8.04, 4.47 km sec^{-1} and 3.30 g cm^{-3}, respectively. Most of stations are located in the first and second quadrants (Fig. 1), but the station coverage does not greatly affect the eventual results obtained in this study, especially for the determination of fault plane solution (cf. Lin et al. 2006).

4. RESULTS

Initially, we search for the minimum misfit between the observed and synthetic seismograms from a succession of source duration to obtain the best source duration for each station. Meanwhile, the pseudo radiation patterns for each station are inverted using Eq. (3). Figure 3 shows several examples of the inversion process. The focal mechanism can be derived by a grid search of the status of the fault at an interval of 1°, noting when the misfit between the theoretical and pseudo radiation patterns has a minimum value (Fig. 4a). The fault plane solutions for the best double couple (strike, dip, slip) are (247°, 17°, 125°) and (31°, 76°, 79°), respectively, and the seismic moment is 4.46 × 10^{19} Nm.

As shown in Fig. 3, we obtain the source duration observed in each station using Eq. (3). The maximum difference of the source duration in Fig. 3 is 4.3 sec (in fact, maximum difference larger than 10 sec), which is significant and indicates the rupture directivity of source. Hence, the fault parameters of the 2005 Miyagi-Oki earthquake can be determined by the rupture directivity analysis [i.e., from Eqs. (4) or (5)]. We test two source models (the unilateral faulting and bilateral faulting models) to determine the appropriate faulting model and fault plane. In this procedure, we find the minimum misfit (i.e., best linear fitting as shown in Fig. 5) for a combination of bilateral faulting and fault plane (247°, 17°, 125°) when searching a series of Θ [rupture azimuths as indicated in Eqs. (4) and (5)]. Thus, the optimal rupture azimuth is estimated at 170° (or 350°) measured counterclockwise from the strike of the fault on the fault plane (Fig. 5). The earthquake rupture apparently follows along the strike of the fault. Taking the P-wave velocity in the source area to be 8.04 km sec^{-1} (cf. Chung and Kanamori

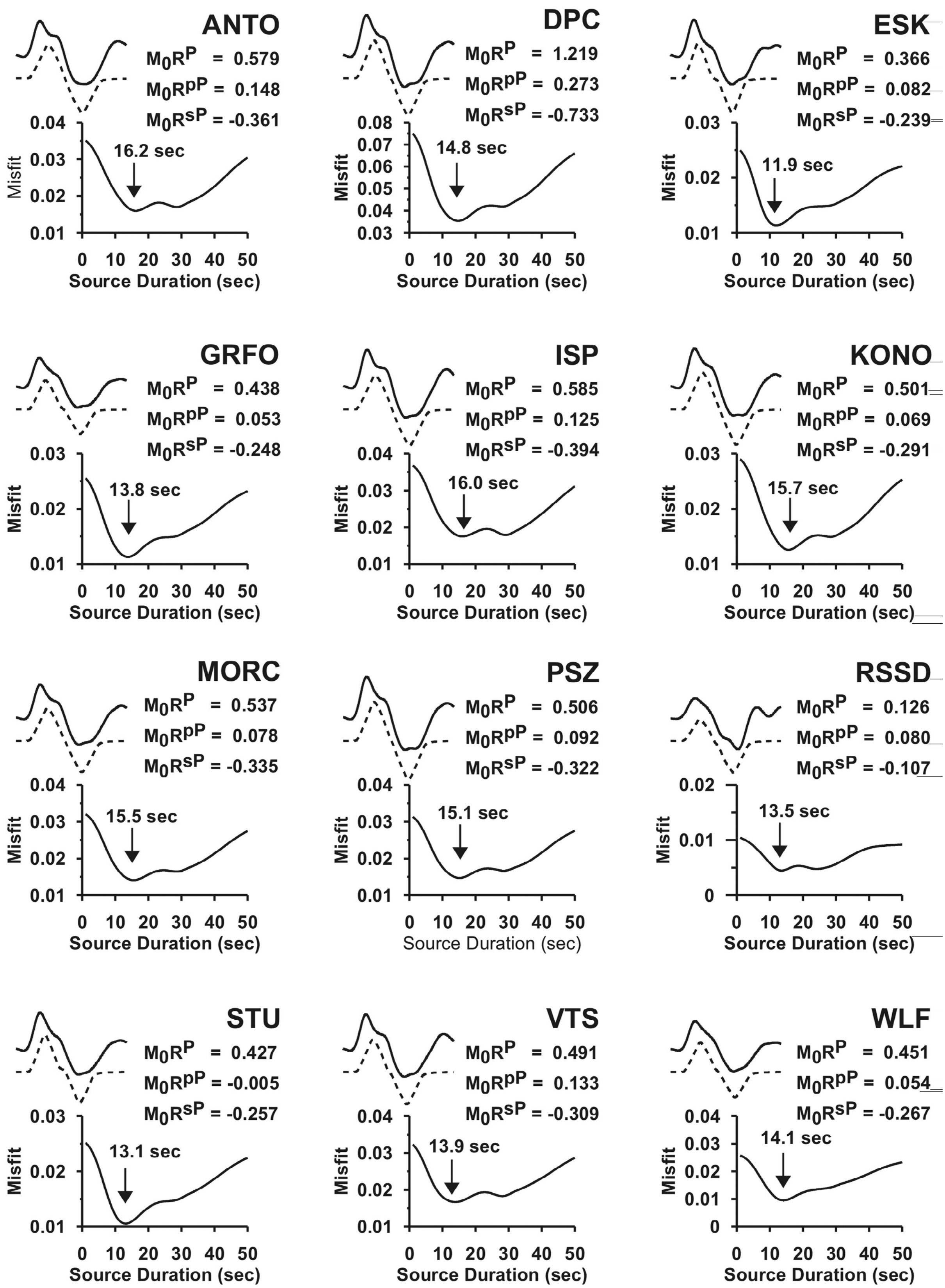

Fig. 3. Map showing the decision of the best source duration according to Lin et al. (2006). The bottom diagram for each station shows the estimate of the best source duration obtained from a successive search of source durations between 1 and 50 sec at 0.1 sec intervals. The arrow denotes the best source duration obtained from the grid search. The top diagram shows a comparison of the observed (solid line) and synthetic (dashed line) P-wave seismograms. Also shown are the station code and pseudo radiation pattern (M_oR^P, M_oR^{pP}, M_oR^{sP}) determined from the best source duration.

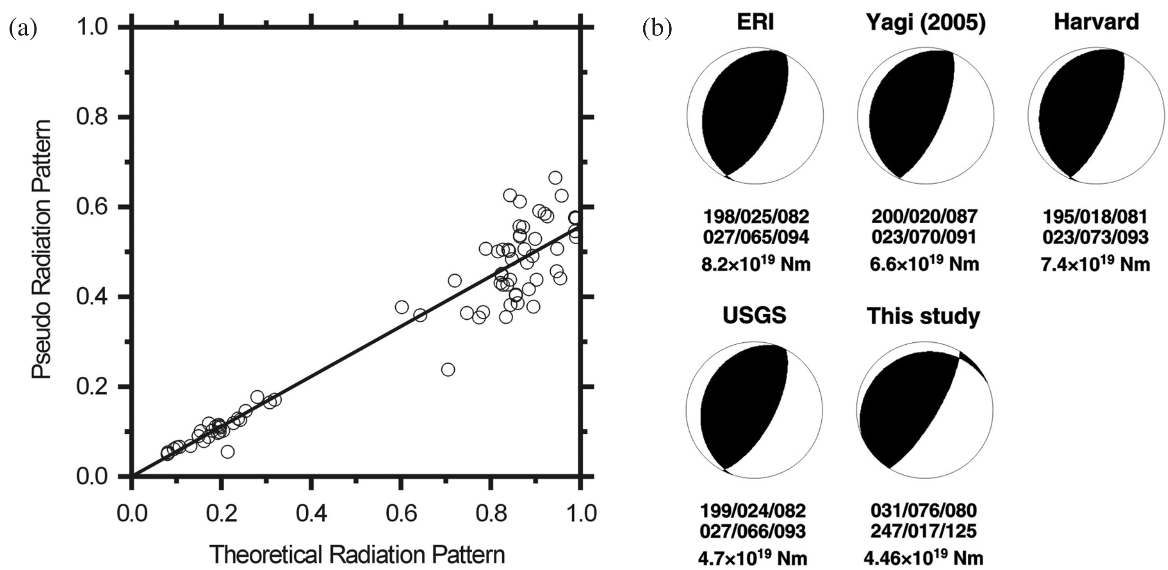

Fig. 4. (a) The best fault plane solution found through a grid search of the status of an earthquake (at an interval of 1°) obtained by comparing the theoretical and pseudo radiation patterns. The solid line indicates the best linear regression and its slope (~0.557) stands for the normalized seismic moment (by 8.0×10^{19} Nm). (b) Comparison of the fault plane solution and seismic moment obtained in our study with those obtained from USGS, Harvard CMT, ERI and Yagi (2005). The corresponding fault plane solution and seismic moment are also shown below each beach ball.

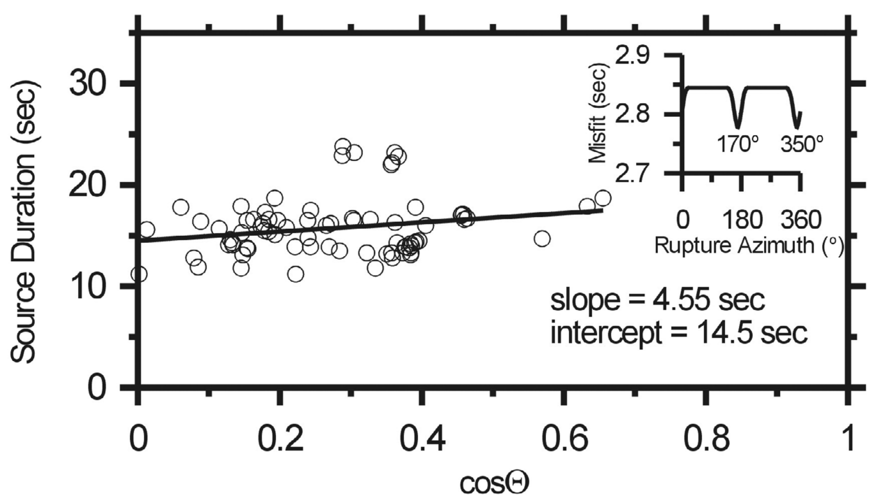

Fig. 5. The analysis shows smaller misfit of rupture direction under bilateral faulting than under unilateral faulting. The source duration is plotted against $\cos\Theta$ as obtained on the basis of the bilateral faulting and the best rupture direction (170° or 350°). Θ is the angle between the rupture direction and ray away from the source. Slope denotes the time for the seismic-wave to propagate through the fault, from the beginning of the faulting to the end of the faulting along the rupture direction. Intercept is the average source duration. The inset denotes the best rupture direction, 170° (or 350°), measured counterclockwise from the strike on the fault plane and obtained from a grid search at 1°-interval.

1976, 1980; Lin et al. 2006; Warren and Shearer 2006), we estimate the rupture length to be 73.4 km from the slope as shown in Fig. 5. The average source duration (intercept in Fig. 5) and rupture velocity are 14.5 sec and 2.53 km sec^{-1}, respectively.

Assuming that $L = 2W$ (L = rupture length, W = rupture width) for large earthquakes (cf. Geller 1976), we can estimate the average dislocation of the 2005 Miyagi-Oki earthquake to be 0.33 m over the whole fault plane using the following formula: $M_o = \mu DA$, where M_o is the seismic moment, μ is the rigidity (5.0×10^{10} Nm^{-2}), A is the area of the fault plane, and D is the average dislocation. Based on Brune's circular source model (Brune 1970), the static stress drop ($\Delta\sigma$) is estimated to be 7.7 bars. In addition, the radiated seismic energy (E_s) is calculated from the average source duration using the method of Vassiliou and Kanamori (1982) to be 5.85×10^{13} Nm. Thus the ratio of radiated seismic energy to seismic moment (E_s/M_o) is about 1.31 ×

10^{-6}. We also estimate the apparent stress (σ_a) at 0.65 bars using: $\sigma_a = \mu(E_s/M_o)$ (Wyss and Brune 1968). The estimated source parameters are listed in Table 1.

5. DISCUSSION

Before inversion through Eq. (3), the original seismograms are normalized by a factor of 8.0×10^{19} Nm. Thus, the inverted pseudo radiation patterns in Fig. 3 are also normalized by this factor. The use of various normalizing factors does not cause differences in results when determining the fault plane solution and the seismic moment (cf. Lin et al. 2006). Because the seismic moment is a constant observed for each station, the pseudo radiation pattern varying with station azimuth represents the variation of radiation pattern in connection with the status of the fault. The focal mechanism obtained in our study is similar to that obtained in several other studies (Harvard CMT; USGS; ERI; Yagi 2005), as shown in Fig. 4b. From the rupture directivity analysis, it can be inferred that the 2005 Miyagi-Oki earthquake was a bilateral faulting event with a rupture direction of 170° (or 350°), almost following the strike of the fault on the fault plane. The models of the coseismic slip distribution from the teleseismic *P*-waves (Yagi 2005; ERI's EIC Seismological Note: No.168) also indicated that the rupture distribution mainly followed along the strike-direction on the fault plane and the large slips close to the epicenter of the main shock. This implies the presence of bilateral extension, which is consistent with our study. In contrast, our results differ slightly from the work of Okada et al. (2005), indicating relatively larger ruptures in the dip-direction on the fault.

Nonetheless, the aftershocks of the 2005 Miyagi-Oki earthquake were distributed along the dip-direction, where a region of weak slip is displayed (Yagi 2005; ERI's EIC Seismological Note: No.168). From the viewpoint of the asperity source model, aftershocks would occur mostly around the region of the main rupture of the fault plane (e.g., Ruff and Kanamori 1983). The slip models from Yagi (2005) and ERI seem to better interpret the connection between the coseismic slip model and the distribution of the aftershocks. The estimated rupture length is about 73.4 km, which is also comparable with both Yagi's result (~90 km) and the ERI report (~60 km), but differs from that obtained by Okada et al. (2005). Our estimate of rupture length is slightly different from Yagi (2005) and ERI and might be regarded as the effective rupture length of the earthquake fault. The average source duration ~14.5 sec is slightly smaller than the results of Yagi (2005), ERI or the Harvard CMT (18 ~ 25 sec). The rupture velocity for this earthquake is estimated to be 2.53 km sec^{-1}, ~0.57 Vs (Vs = 4.47 km sec^{-1} in the source area), also slower than that for similarly sized earthquakes (~0.8 - 0.9 times the *S*-wave velocity). A slow rupture velocity might convey information suggesting the need for a tsunami warning.

The estimated E_s/M_o, 1.31×10^{-6} coincides with that found by Pérez-Campos and Beroza (2001) for reverse earthquakes, but is still lower than global observations (Choy and Boatwright 1995) and about 4 times as small as that given in a USGS report. It is likely that the E_s (Table 1) estimated from the simple source time function in this study may have been underestimated as a result of the elimination of high-frequency energies (e.g., Kikuchi and Fukao 1988; Bilek et al. 2004). This is the so-called finite frequency bandwidth limitation, which is a problem when estimating the radiated seismic energy from seismic waveforms (Boore 1986; Di Bona and Rovelli 1988; Ide and Beroza 2001; Wang 2004; Wang and Huang 2007). However, when calculating the E_s from the source duration by using the method of Vassiliou and Kanamori (1982), one cannot introduce the finite frequency bandwidth limitation to estimates of E_s. Multiple event analysis might improve the estimation of E_s to some degree when using Vassiliou and Kanamori's method (e.g., Kikuchi and Fukao 1988; Hwang et al. 2008; Hwang and Wu 2009).

The estimated static stress drop, 7.7 bars, corresponds to the value for interplate earthquakes (Kanamori and Anderson 1975), but differs from that (17.0 bars) estimated from a fault area of 60-km × 40-km and a seismic moment of 8.2×10^{19} Nm based on the ERI report. The estimated apparent stress (0.65 bars) of the 2005 Miyagi-Oki earthquake agrees well with that for reverse events (~1.5 bars) found by Pérez-Campos and Beroza (2001). Kanamori and Rivera (2004) stated that E_s/M_o is related to the cube of the rupture velocity and static stress drop. A relationship among the minimum E_s/M_o (i.e., the lower bound of E_s/M_o), the rupture velocity and the static stress drop de-

Table 1. Source parameters estimated in this study.

Fault plane solution (strike/dip/slip)	247°/17°/125°
Seismic moment (M_o)	4.46×10^{19} Nm
Rupture length (L)	73.4 km
Average source duration	14.5 sec
Rupture azimuth [*]	170° (or 350°)
Rupture velocity (V_r)	2.53 km sec^{-1}
Static stress drop ($\Delta\sigma$)	7.7 bars
Apparent stress (σ_a)	0.65 bars
Radiated seismic energy (E_s)	5.85×10^{13} Nm
E_s/M_o	1.31×10^{-6}

[*] *The rupture azimuth is measured counterclockwise from the strike of the fault on the fault plane.*

rived by Kanamori and Rivera (2004) can be formulated as $(E_s/M_o)_{\min} = 0.87(1/\mu\beta^3)(\Delta\sigma V_R^3)$, where μ the shear modulus, β the S-wave velocity, $\Delta\sigma$ the static stress drop, and V_R the rupture velocity. When $\Delta\sigma = 7.7$ bars, $V = 2.53$ km sec^{-1}, $\beta = 4.47$ km sec^{-1} and $\mu = 6.6 \times 10^{10}$ Nm^{-2} in our study, the value of $(E_s/M_o)_{\min}$ is calculated to be about 1.84×10^{-6}. This is close to our estimate of E_s/M_o. If we use $E_s = 3.8 \times 10^{14}$ Nm from the USGS report, and $M_o = 8.2 \times 10^{19}$ Nm and $\Delta\sigma = 15$ bars from the ERI report, the estimated rupture velocity is about 3.08 km sec^{-1}, ~0.69 Vs (Vs = 4.47 km sec^{-1} in the source area), from the above-mentioned formula (Kanamori and Rivera 2004). This value is also smaller for this earthquake than those for large earthquakes (~0.9 Vs) (Kanamori and Heaton 2000; Kanamori and Rivera 2004). Additionally, estimates of rupture velocity seem to be slow from the slip distribution of Yagi (2005) and the ERI report. The two models show that the 2005 Miyagi-Oki earthquake is a bilateral faulting event and has source duration of 25 sec. From their fault dimensions, the average rupture velocity is probably 1.5 - 2.0 km sec^{-1}. Hence, we suggest that the low E_s and E_s/M_o might be due to the occurrence of slow rupturing during the earthquake faulting, resulting in the suppression of high-frequency energies. In addition, it should be noted that our results seem to be similar to those indicating tsunami earthquakes (Newman and Okal 1998; Bilek et al. 2004). On the other hand, the estimated E_s/M_o approximates that of an underthrusting type of earthquakes occurring in shallow subduction zones (Pérez-Campos and Beroza 2001; Bilek et al. 2004). The slow rupture velocity also leads to smaller radiation efficiency, ranging from ~0.32 - 0.48, obtained from simple energy considerations and a Model III crack (cf. Venkataraman and Kanamori 2004). The lower radiation efficiency reflects the fact that relatively higher fracture energy occurred during the 2005 Miyagi-Oki earthquake relative to the radiated seismic energy.

Providing that the rise time is 0.1 - 0.2 times as large as the whole source duration (Kanamori and Anderson 1975; Geller 1976), we also estimate the average particle velocity associated with the dynamic stress drop to be ~11 - 22 cm sec^{-1}, which is much lower than the value for same-sized earthquakes (Kanamori 1994). The low particle velocity suggests a low dynamic stress drop; in other words, high dynamic friction occurred during the 2005 Miyagi-Oki earthquake faulting. This meant that most of the strain energy due to the stress relaxation was transformed into heat. Furthermore, the lower apparent stress suggests a lower seismic efficiency for the Miyagi-Oki earthquake (Kikuchi and Fukao 1988). The apparent stress is smaller than half of its static stress drop (cf. Zúñiga 1993); this implies that the frictional overshoot stress model can be used to interpret the rupture behavior of the 2005 Miyagi-Oki earthquake. In this case, a lower percentage of strain energy will be transformed into seismic-wave energy.

6. CONCLUSIONS

Large earthquakes frequently occur in northeastern Japan where their rupture areas overlap and cover each other (Yamanaka and Kikuchi 2004). Okada et al. (2005) noted that the 2005 Miyagi-Oki earthquake ruptured the source area of the 1978 event. We investigate the source parameters of the 2005 Miyagi-Oki earthquake from teleseismic P-waves inversion based on the method of Lin et al. (2006). Our results indicate that this earthquake is a bilateral faulting event, and the findings coincide with those from several other studies (Yagi 2005; ERI's report). The macroscopic source parameters from our study suggest that the low particle velocity, low dynamic stress drop, low E_s, and low E_s/M_o of the 2005 Miyagi-Oki earthquake were due to the obstruction of the 1978 event. In other words, it would take more energy to drive the faulting during the rupturing of the 2005 Miyagi-Oki earthquake in the locked source area where the 1978 event occurred. For this reason, the 2005 Miyagi-Oki earthquake had a relatively larger fracture energy, low dynamic stress drop, and low rupture velocity. Because $(\sigma_a/\Delta\sigma) < 0.5$ (cf. Zúñiga 1993), our results also suggest that the stress model of frictional overshoot can be used to interpret the rupture of the 2005 Miyagi-Oki earthquake.

Acknowledgements We extend our thanks for the use of the facilities of the IRIS Data Management System, and specifically the IRIS Data Management Center who gave us access to the waveform and metadata required for this study. The IRIS DMS is funded by the National Science Foundation, specifically by the GEO Directorate through the Instrumentation, under Cooperative Agreement EAR-0004370. We also give special thanks to the two anonymous reviewers for critical suggestions in improving the readability of the manuscript. This study was funded by the National Science Council, ROC, under Grant Nos. NSC91-2119-M-432-001 and NSC92-2119-M-238-002.

REFERENCES

Aki, K. and P. G. Richards, 1980: Quantitative Seismology: Theory and Methods, W. H. Freeman, San Francisco, 932 pp.

Ammon, C. J., A. A. Velasco, and T. Lay, 1993: Rapid estimation of rupture directivity: Application to the 1992 Landers ($M_s = 7.4$) and Cap Mendocino ($M_s = 7.2$), California earthquakes. *Geophys. Res. Lett.*, **20**, 97-100, doi: 10.1029/92GL03032. [Link]

Ben-Menahem, A., 1961: Relation of seismic surface-waves from finite moving sources. *Bull. Seismol. Soc. Am.*, **51**, 401-435.

Bilek, S. L., T. Lay, and L. J. Ruff, 2004: Radiation seismic energy and earthquake source duration variations from teleseismic source time functions for shallow subduction zone thrust earthquakes. *J. Geophys. Res.*, **109**, B09308, doi: 10.1029/2004JB003039. [Link]

Boore, D. M., 1986: The effect of finite bandwidth on seismic scaling relationships. In: Das, S. J. Boatwright, and C. H. Scholz (Eds.), Earthquake Source Mechanism, AGU Geophys. Mono., 37, AGU, Washington, DC, 275-283.

Brune, J. N., 1970: Tectonic stress and the spectra of seismic shear wave from earthquakes. *J. Geophys. Res.*, **75**, 4997-5009, doi: 10.1029/JB075i026p04997. [Link]

Choy, G. L. and J. L. Boatwright, 1995: Global patterns of radiated seismic energy and apparent stress. *J. Geophys. Res.*, **100**, 18205-18228, doi: 10.1029/95JB01969. [Link]

Chung, W. Y. and H. Kanamori, 1976: Source process and tectonic implications of the Spanish deep-focus earthquake of March 29, 1954. *Phys. Earth Planet. Inter.*, **13**, 85-96, doi: 10.1016/0031-9201(76)90073-X. [Link]

Chung, W. Y. and H. Kanamori, 1980: Variations of seismic source parameters and stress drops within a descending slab and its implications in plate mechanics. *Phys. Earth Planet. Inter.*, **23**, 134-159, doi: 10.1016/0031-9201(80)90008-4. [Link]

Di Bona, M. and A. Rovelli, 1988: Effects of the bandwidth limitation on stress drops estimated from integrals of the ground motions. *Bull. Seismol. Soc. Am.*, **78**, 1818-1825.

Dziewonski, A. M., T. A. Chou, and J. H. Woodhouse, 1981: Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. *J. Geophys. Res.*, **86**, 2825-2852, doi: 10.1029/JB086iB04p02825. [Link]

Geller, R. J., 1976: Scaling relations for earthquake source parameters and magnitudes. *Bull. Seismol. Soc. Am.*, **66**, 1501-1523.

Hwang, R. D. and J. J. Wu, 2009: Rupture directivity and multiple event analyses of the 2008 Wenchuan (China) earthquake, in 2009 Annu. Congress of Chinese Geophysical Society and Geological Society of Taiwan, Chiayi, Taiwan, 5-6 May 2009.

Hwang, R. D., J. H. Wang, B. S. Huang, K. C. Chen, W. G. Huang, T. M. Chang, H. C. Chiu, and C.-C. P. Tsai, 2001: Estimates of stress drop of the Chi-Chi, Taiwan, earthquake of September 20 1999 from near-field seismograms. *Bull. Seismol. Soc. Am.*, **91**, 1158-1166, doi: 10.1785/0120000708. [Link]

Hwang, R. D., G. K. Yu, T. W. Lin, J. P. Chang, and W. Y. Chang, 2008: Radiated seismic energy of 26 December 2004 Sumatra earthquake estimated from multiple-event analysis, in 2008 Annu. Congress of Chinese Geophysical Society and Geological Society of Taiwan, Tainan, Taiwan, 7-8 May 2008.

Ide, S. and G. C. Beroza, 2001: Does apparent stress vary with earthquake size? *Geophys. Res. Lett.*, **28**, 3349-3352, doi: 10.1029/2001GL013106. [Link]

Kanamori, H., 1994: Mechanics of earthquakes. *Annu. Rev. Earth Planet. Sci.*, **22**, 207-237, doi: 10.1146/annurev.ea.22.050194.001231. [Link]

Kanamori, H. and D. L. Anderson, 1975: Theoretical basis of some empirical relations in seismology. *Bull. Seismol. Soc. Am.*, **65**, 1073-1095.

Kanamori, H. and G. S. Stewart, 1976: Mode of the strain release along the Gibbs fracture zone, Mid-Atlantic ridge. *Phys. Earth Planet. Inter.*, **11**, 312-332, doi: 10.1016/0031-9201(76)90018-2. [Link]

Kanamori, H. and T. H. Heaton, 2000: Microscopic and macroscopic physics of earthquakes. In: Rundle, J., D. L. Turcotte, and W. Klein (Eds.), Geocomplexity and the Physics of Earthquakes, AGU Geophys. Mono., 120, Washington, DC, 147-163.

Kanamori, H. and L. Rivera, 2004: Static and dynamic scaling relations for earthquakes and their implications for rupture speed and stress drop. *Bull. Seismol. Soc. Am.*, **94**, 314-319, doi: 10.1785/0120030159. [Link]

Kennett, B. L. N. and E. R. Engdahl, 1991: Traveltimes for global earthquake location and phase identification. *Geophys. J. Int.*, **105**, 429-465, doi: 10.1111/j.1365-246X.1991.tb06724.x. [Link]

Kikuchi, M. and Y. Fukao, 1988: Seismic wave energy inferred from long-period body wave inversion. *Bull. Seismol. Soc. Am.* **78**, 1707-1724.

Lin, T. W., R. D. Hwang, K. F. Ma, and Y. B. Tsai, 2006: Simultaneous determination of source parameters using far-field P waves: Focal mechanism, seismic moment, rupture length and rupture velocity. *Terr. Atmos. Ocean. Sci.*, **17**, 463-487.

Menke, W., 1984: Geophysical Data Analysis: Discrete Inversion Theory, Academic Press, San Diego, 260 pp.

Newman, A. V. and E. A. Okal, 1998: Teleseismic estimates of radiated seismic energy: The E_s/M_o discriminant for tsunami earthquakes. *J. Geophys. Res.*, **103**, 26885-26898, doi: 10.1029/98JB02236. [Link]

Okada, T., T. Yaginuma, N. Umino, T. Kono, T. Matsuzawa, S. Kita, and A. Hasegawa, 2005: The 2005 M7.2 MIYAGI-OKI earthquake, NE, Japan: Possible rerupturing of one of asperities that caused the previous M7.4 earthquake. *Geophys. Res. Lett.*, **32**, L24302, doi: 10.1029/2005GL024613. [Link]

Okal, E. A., 1992: A student's guide to teleseismic body wave amplitude. *Seismol. Res. Lett.*, **63**, 169-180.

Pérez-Campos, X. and G. C. Beroza, 2001: An apparent mechanism dependence of radiated seismic energy. *J. Geophys. Res.*, **106**, 11127-11136, doi: 10.1029/2000JB900455. [Link]

Ruff, L. and H. Kanamori, 1983: The rupture process and asperity distribution of three great earthquakes from long-period diffracted P-waves. *Phys. Earth Planet. In-*

ter., **31**, 202-230, doi: 10.1016/0031-9201(83)90099-7. [Link]

Sipkin, S. A., 1994: Rapid determination of global moment-tensor solutions. *Geophys. Res. Lett.*, **21**, 1667-1670, doi: 10.1029/94GL01429. [Link]

Vassiliou, M. S. and H. Kanamori, 1982: The energy release in earthquakes. *Bull. Seismol. Soc. Am.*, **72**, 371-387.

Venkataraman, A. and H. Kanamori, 2004: Observational constrains on the fracture energy of subduction zone earthquakes. *J. Geophys. Res.*, **109**, B05302, doi: 10.1029/2003JB002549. [Link]

Wang, J. H., 2004: The seismic efficiency of the 1999 Chi-Chi, Taiwan, earthquake. *Geophys. Res. Lett.*, **31**, L10613, doi: 10.1029/2004GL019417. [Link]

Wang, J. H. and M. W. Huang, 2007: Effect of finite frequency bandwidth limitation on evaluations of seismic radiation energy of the 1999 Chi-Chi earthquake. *Terr. Atmos. Ocean. Sci.*, **18**, 567-576 doi: 10.3319/TAO.2007.18.3.567(T). [Link]

Warren, L. M. and P. M. Shearer, 2006: Systematic determination of earthquake rupture directivity and fault planes from analysis of long-period P-wave spectra. *Geophys. J. Int.*, **164**, 46-62, doi: 10.1111/j.1365-246X.2005.02769.x. [Link]

Wyss, M. and J. N. Brune, 1968: Seismic moment, stress, and source dimensions for earthquakes in the California-Nevada region. *J. Geophys. Res.*, **73**, 4681-4694, doi: 10.1029/JB073i014p04681. [Link]

Yagi, Y., 2005: Preliminary Results of Rupture Process for August 16 2005 Miyagi-Oki, Japan, earthquake, posted on http://www.geo.tsukuba.ac.jp/press_HP/yagi/EQ/20050816NorthJapan.

Yamanaka, Y. and M. Kikuchi, 2004: Asperity map along the subduction zone in northeastern Japan inferred from regional seismic data. *J. Geophys. Res.*, **109**, B07307, doi: 10.1029/2003JB002683. [Link]

Yoshida, S., 1988: Waveform inversion for rupture processes of two deep earthquakes in the Izu-Bonin region. *Phys. Earth Planet. Inter.*, **52**, 85-101, doi: 10.1016/0031-9201(88)90058-1. [Link]

Zúñiga, R. F., 1993: Frictional overshoot and partial stress drop. Which one? *Bull. Seismol. Soc. Am.*, **83**, 939-944.