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NOTES AND CORRESPONDENCE

Estimating the Radiated Seismic Energy of the 2010 M_L 6.4 JiaSian, Taiwan, Earthquake Using Multiple-Event Analysis

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ABSTRACT

Through a proposed multiple-event analysis of teleseismic *P*-waves, this study investigated the radiated seismic energy and rupture process of the 2010 JiaSian earthquake. Results showed that the earthquake comprised at least two sub-events. The first sub-event was followed by the second sub-event, ~1.7 s later. The entire source duration was 5.4 s. Let the two sub-events occur on the same fault plane with a strike of 304° and a dip of 28°; the first sub-event had a relatively smaller seismic moment (M_0) and larger radiated seismic energy (E_S) than the second sub-event, and this leads to the E_S/M_0 of the first sub-event larger than that of the second sub-event thus. This feature implies that the first sub-event probably had a higher static stress drop during faulting. The total M_0 was estimated to be 2.17×10^{18} Nm, corresponding to $M_W = 6.15$, and the total E_S was ~2.91×10^{13} Nm, larger than that estimated only from a single source. Subsequently, the E_S/M_0 was approximately 1.3×10^{-5}, lower than ordinary earthquakes. The low static stress drop was probably responsible for the low E_S/M_0. Overall, the 2010 JiaSian earthquake was characterized by a relatively low E_S/M_0 and low static stress drop, and then the partial stress drop model would be relatively appropriate to interpret its rupture process.

Key words: JiaSian earthquake, Radiated seismic energy, Multiple-event analysis

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1. INTRODUCTION

In terms of historical seismicity, southwestern Taiwan is a region of interest with regard to seismic hazard. Several disastrous earthquakes have occurred in southern Taiwan, such as the 1906 MeiShan earthquake, the 1941 ChungPu earthquake, the 1964 PaiHo earthquake, the 1998 RueyLi earthquake, the 1999 ChiaYi earthquake, and the 2006 PingTung earthquake (refer to the CWB's website: http://www.cwb.gov.tw/V7/earthquake/damage_eq.htm). On March 4, 2010, a moderate-sized earthquake with M_L = 6.4 (as reported from the CWB), occurring in a region of low seismicity surrounded by high seismicity, struck southwestern Taiwan (Hsu et al. 2011; Huang et al. 2011). This event was called the 2010 JiaSian earthquake (Fig. 1). The earthquake occurred initially at a depth of approximately 23 km and ruptured with a thrust mechanism (Huang et al. 2011; Hwang et al. 2012). Its aftershocks were distributed northwestward (Fig. 1) and suggested that the strike of the earthquake should be associated with the ChiShan transfer fault zone (CTFZ), not the ChaoChou fault CCF (Ching et al. 2011; Huang et al. 2011). In other words, the JiaSian earthquake occurred on an unknown fault. Hsu et al. (2011) suggested that the JiaSian earthquake encourages failures on the ChuKou fault from the calculated Coulomb stress changes. According to rupture directivity analysis, Hwang et al. (2012) further demonstrated that the earthquake was a unilateral faulting event with high rupture velocity on the NW-striking fault plane. Lee et al. (2012) derived a more complex source model of the JiaSian earthquake, including three main ruptures, from joint inversion of teleseismic and near field data than those only from GPS data (Ching et al.

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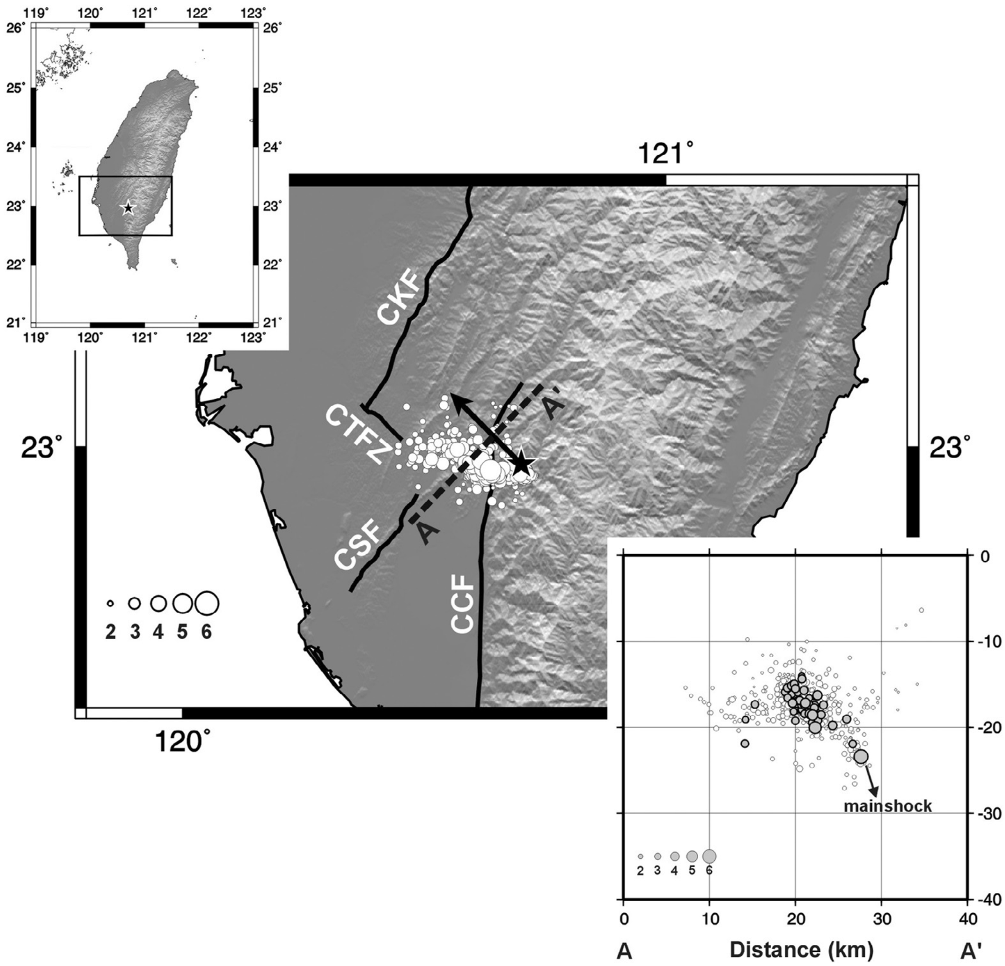

Fig. 1. The star denotes the epicenter of the main shock and the solid circles denote the aftershocks, which occurred within one day. The size of circle is proportional to magnitude (M_L). The arrow indicates the rupture direction on the surface from the rupture directivity analysis (Hwang et al. 2012). The solid lines represent main faults in the source area, including the ChaoChou fault (CCF), the ChiShan fault (CSF), the ChuKou fault (CKF), and the ChiShan transfer fault zone (CTFZ). Line AA', normal to the rupture direction, is the location of cross section. Included also is the cross section of aftershocks vs. depth along line AA'. The gray circles are the aftershocks with $M_L \geq 3.0$.

2011; Hsu et al. 2011). A special feature of the 2010 JiaSian earthquake is a low static stress drop of approximately 5 bars, which was derived from GPS data using an elastic uniform stress drop inversion by Ching et al. (2011). Such a low stress drop for the JiaSian earthquake departs from the values (30 - 100 bars) for the so-called interplate and intraplate earthquakes (Kanamori and Anderson 1975), but is comparable with a reciprocal relationship between stress drop and rupture velocity (Tan and Helmberger 2010). A low stress drop is therefore relative to a high rupture velocity for the 2010 JiaSian earthquake (Hwang et al. 2012).

In addition to the above-mentioned rupture feature of the 2010 JiaSian earthquake, the radiated seismic energy (E_S), a macroscopic source parameter, can also provide important information to understand the dynamic rupture of earthquakes (cf. Zúñiga 1993; Kanamori and Heaton 2000; Hwang et al. 2001, 2010; Venkataraman and Kanamori 2004). The ratio (E_S/M_0) of radiated seismic energy to seismic moment (M_0) is related to the dynamics of earthquake faulting (cf. Kanamori and Heaton 2000). To date, E_S estimates come from the integral of seismic waves or from a source time function (e.g., Vassiliou and Kanamori 1982; Kikuchi and Fukao 1988; Choy and Boatwright 1995; Hwang et al. 2001, 2010, 2012; Bilek et al. 2004; Venkataraman and Kanamori 2004). However, E_S might be underestimated when the complexity of the source is ignored (Kikuchi and Fukao 1988; Bilek et al. 2004) as well as the effect of finite frequency bandwidth (Ide and Beroza 2001; Wang 2004). However, the multiple event analysis might improve E_S estimates to some degree (e.g., Kikuchi and Fukao 1988; Hwang et al. 2008). Earlier, Hwang et al. (2012) used a single source to determine $E_S = 1.0 \times 10^{13}$ Nm for the JiaSian earthquake, which is lower than the USGS report (1.7×10^{13} Nm).

In Fig. 2, multiple events are evident at a few stations with an azimuth of approximately 0° - 180°. In these stations, the P-wave was composed of at least two sub-events, as shown in E1 (the first sub-event) and E2 (the second sub-event) at station WRKA (Fig. 2). Hence, in this study, we set two sub-events into the 2010 JiaSian earthquake to reexamine its rupture features and radiated seismic energy by a proposed multiple-event analysis.

2. DATA

Teleseismic P-waves, used to investigate the 2010 JiaSian earthquake, were provided by the Incorporated Research Institutions for Seismology Data Management Center (IRIS DMC). This study used only seismograms at epicentral distances of 30° - 90° in order to eliminate the interference of core phases (as the PcP-wave) and multi-pathing waves (as the PP-wave). The P-wave train from vertical-component recordings for the multiple-event analysis is 35 s long (5 s before and 30 s after the P-arrival). Finally, each seismogram was converted to displacement after removing the instrumental response, and then filtered between 0.01 and 0.5 Hz. Figure 2 shows the 28 stations used in this study.

3. ANALYSIS AND RESULTS

3.1 Multiple-Event Analysis

For a shallow focal depth, the direct P-wave is followed closely by two depth phases, pP- and sP-waves. Hence, at a given receiver, a teleseismic synthetic P-wave, $u^P(t)$, can be written as follows (cf. Kanamori and Stewart 1976; Okal 1992; Lin et al. 2006; Hwang et al. 2010, 2012).

$$\begin{aligned} u^P(t) &= \frac{M_0}{4\pi\rho_h\alpha_h^3}\cdot\frac{g(\Delta)}{r}\cdot C^P(i_0)\cdot\Big[R^P f(t-t_P)+ \\ &\quad R^{pP}V_{pP}f(t-t_{pP})+R^{sP}\frac{\alpha_h\cos i_h}{\beta_h\cos j_h}V_{sP}f(t-t_{sP})\Big]*Q(t) \\ &= PARA\cdot[M_0R^P\cdot A_P(t)+M_0R^{pP}\cdot A_{pP}(t)+ \\ &\quad M_0R^{sP}\cdot A_{sP}(t)] \end{aligned} \tag{1}$$

$$PARA=\frac{1}{4\pi\rho_h\alpha_h^3}\cdot\frac{g(\Delta)}{r}\cdot C^P(i_0)$$

$$A_P(t)=f(t-t_P)*Q(t)$$

$$A_{pP}(t)=V_{pP}f(t-t_{pP})*Q(t)$$

$$A_{sP}(t)=\frac{\alpha_h\cos i_h}{\beta_h\cos j_h}V_{sP}f(t-t_{sP})*Q(t)$$

M_0: the seismic moment;
$\alpha_h, \beta_h, \rho_h$: the P-wave velocity, S-wave velocity, and density of the source area;
$g(\Delta)$: the geometrical spreading factor, related to the epicentral distance (Δ) and focal depth;
r: the radius of the Earth (6371 km);
R^P, R^{pP}, R^{sP}: the radiation patterns for the P-, pP- and sP-waves;
V_{pP}, V_{sP}: the reflection coefficients of the P- to P-wave and the S- to P-wave on the free surface;
i_h, j_h: the takeoff angles of P- and S-waves leaving the source;
i_0: the incident angle of P-wave regarding the free surface;
$C^P(i_0)$: the free surface effect at the receiver as a function of i_0;
$f(t)$: a triangular source time function, a single source, used in this study;
t_P, t_{pP}, t_{sP}: the travel times for the P-, pP-, and sP-waves;
$Q(t)$: the attenuation filter.

In Eq. (1), $u^P(t)$ is not inclusive of the instrumental effect. From Fig. 2, we set two sub-events, $u_1^P(t)$ and $u_2^P(t)$, with a time lag of Δt to Eq. (1). Thus, the proposed synthetic P-wave due to multiple events is:

$$\begin{aligned} u^P(t) &= u_1^P(t)+u_2^P(t) \\ &= PARA1\cdot[M_{01}R_1^P\cdot A_{P1}(t)+M_{01}R_1^{pP}\cdot A_{pP1}(t)+ \\ &\quad M_{01}R_1^{sP}\cdot A_{sP1}(t)]+PARA2\cdot[M_{02}R_2^P\cdot A_{P2}(t+\Delta t)+ \\ &\quad M_{02}R_2^{pP}\cdot A_{pP2}(t+\Delta t)+M_{02}R_2^{sP}\cdot A_{sP2}(t+\Delta t)] \end{aligned} \tag{2}$$

where numbers "1" and "2" indicate the parameters from the first and second sub-events, respectively; $(M_{01}R_1^P, M_{01}R_1^{pP}, M_{01}R_1^{sP})$ and $(M_{02}R_2^P, M_{02}R_2^{pP}, M_{02}R_2^{sP})$ are the unknown parameters (i.e., pseudo radiation patterns), requested to be resolved using the inversion, for the first and second sub-events. Following Lin et al. (2006) and Hwang et al. (2010, 2012), for convenience in inversion, Eq. (2) is rewritten into the following matrix form with n data points.

$$\begin{bmatrix} PARA1\cdot F_{P1}(t_1) & PARA2\cdot F_{P2}(t_1+\Delta t) \\ PARA1\cdot F_{P1}(t_2) & PARA2\cdot F_{P2}(t_2+\Delta t) \\ \vdots & \vdots \\ PARA1\cdot F_{P1}(t_n) & PARA2\cdot F_{P2}(t_n+\Delta t) \end{bmatrix}\cdot\begin{bmatrix} M_{01}R_1^P \\ M_{01}R_1^{pP} \\ M_{01}R_1^{sP} \\ ----- \\ M_{02}R_2^P \\ M_{02}R_2^{pP} \\ M_{02}R_2^{sP} \end{bmatrix}=\begin{bmatrix} u^P(t_1) \\ u^P(t_2) \\ \vdots \\ u^P(t_n) \end{bmatrix} \tag{3}$$

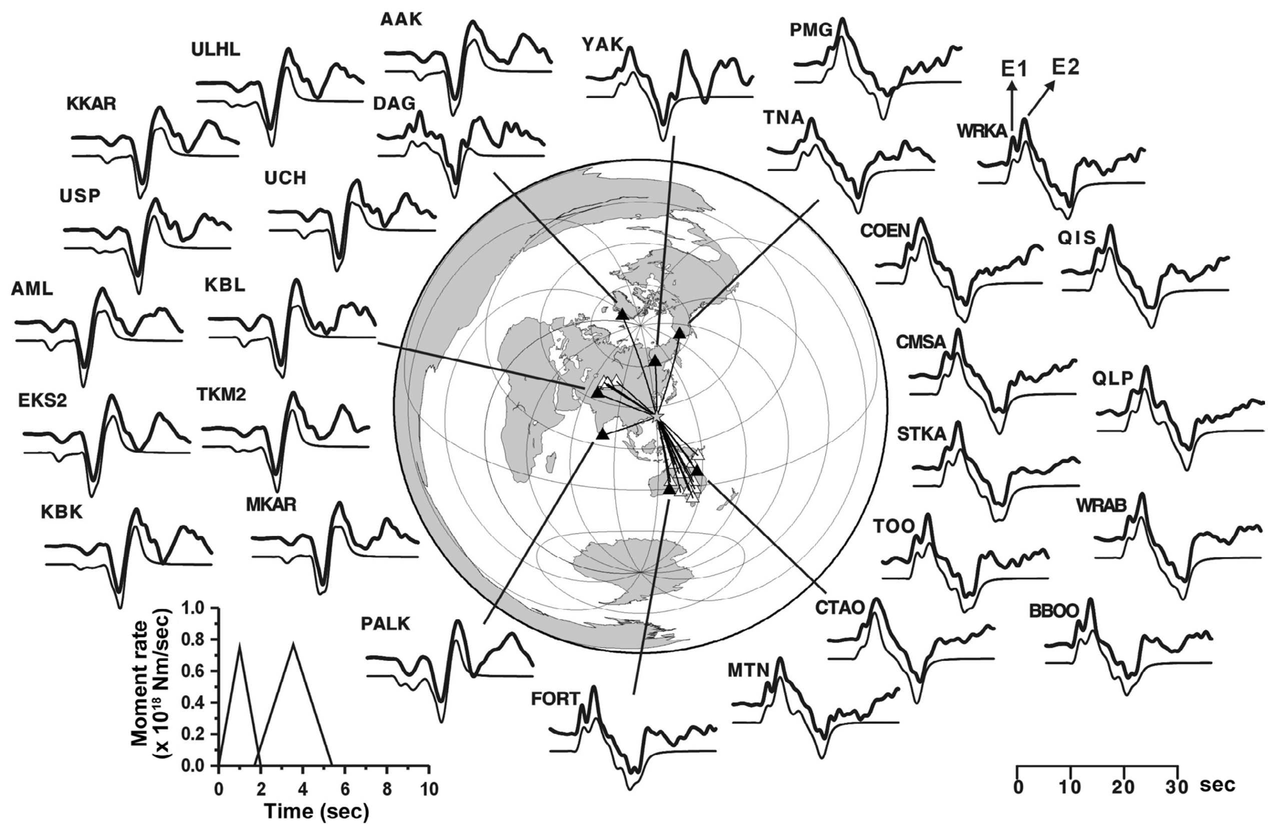

Fig. 2. The map showing the distribution of the stations used and a comparison of observed (thick lines) and synthetic (thin lines) *P*-waves. The star is the epicenter of the main shock. Six stations are marked to display the *P*-wave modeling at various azimuth angles. Included also is the source time function in the lower left of the diagram. E1 and E2, displayed in station WRKA, demonstrate two sub-events during the JiaSian earthquake.

where $F_{P1}(t) = [A_{P1}(t)\ \ A_{pP1}(t)\ \ A_{sP1}(t)]$ and $F_{P2}(t+\Delta t) = [A_{P2}(t+\Delta t)\ \ A_{pP2}(t+\Delta t)\ \ A_{sP2}(t+\Delta t)]$.

Searching for the source duration of the two sub-events and the time lag of Δt completes inversion to retrieve the appropriate pseudo radiation patterns, source duration, and time lag for the two sub-events when the misfit reaches a minimum value between observed and synthetic *P*-waves.

Hwang et al. (2012) reexamined the source parameters of the 2010 JiaSina earthquake to state that the earthquake occurred initially at a depth of 22 km (e.g., Huang et al. 2011) and ruptured later at a depth of 20 km. Therefore, following their results, the first sub-event (E1) was fixed at a 22-km depth and the second sub-event (E2) was located at a 20-km depth. A few related parameters for the two sub-events in the inversion, as in Eqs. (1) and (2), are calculated theoretically using the *iasp*91 velocity model (Kennett and Engdahl 1991) and an average attenuation parameter of $t^* = 1.0$ for the *P*-wave propagation (e.g., Okal 1992; Aki and Richards 2002). Searching for the source duration and time lag through Eq. (3) shows that E1 had a source duration of 2.0 s and approximately 1.7 s later E2 with a source duration of 3.7 s occurred subsequently (Fig. 2). Hence, the entire source duration for the JiaSian earthquake was 5.4 s. Figure 2 shows a comparison of observed and synthetic *P*-waves. To begin with, the first arrivals of observed *P*-waves were picked, so the synthetic *P*-waves were modeled at stations from the onset of *P*-wave rather than from the hypocenter. For this reason, the lateral variations in structures, producing the various propagation times of *P*-waves at stations, can be neglected in the calculation of the synthetic *P*-waves when using the 1-D *iasp*91 model. In this analysis, the pseudo radiation patterns for the two sub-events were inverted by Eq. (3) (cf. Lin et al. 2006; Hwang et al. 2010, 2012). Fixing the strike and dip angle of the fault plane at 304° and 28° according to the work of Hwang et al. (2012) to derive the seismic moments using the inverted pseudo radiation patterns; meanwhile, this study also made the rake angle variable for the two sub-events. Thus, E1 had $M_0 = 0.75 \times 10^{18}$ Nm ($M_W = 5.8$) and a rake of 39°; $M_0 = 1.42 \times 10^{18}$ Nm ($M_W = 6.0$) and a rake of 45° for the E2. The total seismic moment is 2.17×10^{18} Nm ($M_W = 6.15$). Table 1 lists source parameters for the two sub-events from multiple-event analysis.

3.2 Radiated Seismic Energy

Vassiliou and Kanamori (1982) proposed the estimation of radiated seismic energy (E_S) from an integral of a

Table 1. Source parameters for the 2010 JiaSian earthquake from the multiple event analysis.

Event No.	fault plane (strike/dip/rake)	delay-time to E1 (s)	source duration (s)	M_0 (Nm)	E_S (Nm)	E_S/M_0
E1	304°/28°/39°	0.0	2.0	0.75×10^{18}	1.86×10^{13}	2.5×10^{-5}
E2	304°/28°/45°	1.7	3.7	1.42×10^{18}	1.05×10^{13}	7.4×10^{-6}
Total	-	-	5.4	2.17×10^{18}	2.91×10^{13}	1.3×10^{-5}

squared trapezoid-type moment-rate function as follows:

$$E_S = \left[\frac{1}{15\pi\rho\alpha^5} + \frac{1}{10\pi\rho\beta^5}\right]\frac{2}{x(1-x)^2}\frac{M_0^2}{T_0^3} \tag{4}$$

where α, β, and ρ, are the P-wave velocity, S-wave velocity, and density, respectively, at the source area. M_0 and T_0 are the seismic moment and source duration. For a trapezoid-type source time function, Vassiliou and Kanamori (1982) used $x = 0.2$, that is, rise time $= xT_0 = 0.2T_0$, following observations of large earthquakes (Geller 1976). For a triangular source time function used in this study, x is 0.5. At $x = 0.2$, the factor $x(1 - x)^2 = 0.128$ in Eq. (4); at $x = 0.5$, $x(1 - x)^2 = 0.125$. Under the same M_0 and T_0, therefore, the two E_S determined by $x = 0.2$ and $x = 0.5$ are identical in value.

Taking the P-wave of 6.5 km s^{-1}, S-wave of 3.75 km s^{-1} and density of 2.71 g cm^{-3} in the source area based on the *iasp*91 velocity model yielded $E_S = 1.86 \times 10^{13}$ Nm using $M_0 = 0.75 \times 10^{18}$ Nm and $T_0 = 2.0$ s for the E1, and $E_S = 1.05 \times 10^{13}$ Nm using $M_0 = 1.86 \times 10^{18}$ Nm and $T_0 = 3.7$ s for the E2. The total E_S is 2.91×10^{13} Nm; then $E_S/M_0 = 1.3 \times 10^{-5}$ (see Table 1).

4. DISCUSSION AND CONCLUSIONS

The 2010 JiaSian earthquake comprised at least two sub-events (Fig. 2). The multiple-event analysis shows that E2 followed E1 by approximately 1.7 s, and E2 had a larger source duration. Under the assumption that the two sub-events occurred on the same fault with a strike of 304° and a dip of 28°, the seismic moment for E2 is approximately twice as large as that for E1, whereas the E_S of E1 is larger than that of E2 (Table 1). The total seismic moment, 2.71 $\times 10^{18}$ Nm (M_W = 6.15), is comparable with those of previous studies (Ching et al. 2011; Hsu et al. 2011; Hwang et al. 2012) and reports from the CWB CMT, BATS, USGS, and GCMT. The total source duration of 5.4 s also agrees with estimations from the back-projection of the P-wave envelope (Chao et al. 2011) and rupture directivity analysis of teleseismic P-waves (Hwang et al. 2012). However, the estimated source duration is shorter than that inverted by Lee et al. (2012). The estimated rake angles for the E1 and E2 are 39° and 45°, also leading to thrust faulting for the rupture process of the two sub-events.

Because of the relatively shorter source duration for E1, its E_S is larger than that of E2. Similarly, the E_S/M_0 of E1 is also larger than that of E2 (Table 1). This implies various states of stress during the two sub-events. Probably, E1 has a relatively higher static stress drop during faulting, due to its larger E_S/M_0 (cf. Kanamori and Rivera 2004). The total E_S is 2.91×10^{13} Nm, leading to $E_S/M_0 = 1.3 \times 10^{-5}$, corresponding with global observations (1.6×10^{-5}) of Choy and Boatwright (1995), but lower than others ($3 - 5 \times 10^{-5}$) (Vassiliou and Kanamori 1982; Kanamori and Heaton 2000; Ide et al. 2001; Venkataraman and Kanamori 2004). The total E_S for the JiaSian earthquake is also higher than the USGS report (1.7×10^{13} Nm) and ~3 times larger than the estimation of Hwang et al. (2012) from a single source. This seems to regain the high-frequency energy to some degree from the proposed multiple-event analysis (Kikuchi and Fukao 1988; Hwang et al. 2008) while ignoring the effect of finite frequency bandwidth (Ide et al. 2001; Wang 2004). Following Kanamori and Rivera's suggestion, $(E_S/M_0)_{\min} = 0.87(V_R/\beta)^3(\Delta\sigma_s/\mu)$, where μ is the shear modulus, β is the S-wave velocity, $\Delta\sigma_s$ is the static stress drop, and V_R is the rupture velocity, the static stress drop is estimated to be approximately 5.7 bars by taking $E_S/M_0 = 1.3 \times 10^{-5}$, $\mu = 3.8 \times 10^{10}$ Nm^{-2} and $V_R/\beta = 1.0$ (Hwang et al. 2012). The static stress drop is close to the value (~5 bars) from the inversion of GPS data yielded by Ching et al. (2011). The 2010 JiaSian earthquake is therefore a low static stress drop event relative to a high rupture velocity (e.g., Tan and Helmberger 2010; Hwang et al. 2012). Such a low static stress drop for the JiaSian earthquake lapses from the values for the interplate and intraplate earthquakes (Kanamori and Anderson 1975). Additionally, the low E_S/M_0 of the JiaSian earthquake, also departing from Kanamori and Heaton's suggestions, is due to its low static stress drop. Following Wyss and Brune (1968), the apparent stress (σ_a) is ~5 bars, exceeding half the static stress drop. Because $(\sigma_a/\Delta\sigma_s) > 0.5$, the JiaSian earthquake is better interpreted by the partial stress drop model that final stress is greater than frictional stress (e.g., Zúñiga 1993). Such feature for the 2010 JiaSian earthquake is different from the case of the 1999 Chi-Chi earthquake in Taiwan (Hwang et al. 2001).

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