Earth Planets Space, **63**, 427–434, 2011

Rise time and source duration of the 2008 M_W 7.9 Wenchuan (China) earthquake as revealed by Rayleigh waves

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(Received May 6, 2010; Revised January 11, 2011; Accepted January 12, 2011; Online published June 21, 2011)

The fault parameters of the 2008 Wenchuan earthquake were studied in a rupture directivity analysis by simultaneously inverting the period of the first Fourier spectral-node and the 100-s phase-delay time of the Rayleigh wave. The results show that the earthquake is a unilateral event with an optimal rupture azimuth of N59°E, consistent with the distribution of aftershocks. They also indicate that the fault plane strike is in the NE-SW direction, corresponding to the fault plane strike of 238° and NW-dipping (reported by the USGS). The inversion shows the source duration (including the rise time and rupture time) and rise time are 70±0.8 s and 9.3±0.6 s, respectively. The rupture velocity estimated only from the rupture time exhibits relatively higher value, 3.45±0.10 km/s, close to or larger than the S-wave velocity in the crust. One possible cause is that the rupture mechanism transferred from the thrust faulting in the southwestern portion of the fault to the strike-slip faulting in the northeastern one. The rise time offers an estimate of the dynamic stress drop (37.8±2.3 bars), from which through a macroscopic view the radiated seismic energy of (5.93±0.4) $\times$ 10^{16} N m is calculated. Although the estimated rupture length (∼210 km) and source duration are shorter than several source rupture models, the current analyses show the first-order rupture feature of the 2008 Wenchuan earthquake rupturing the Longmenshan fault zone.

Key words: Rise time, source duration, Rayleigh waves, phase velocity, rupture directivity.

1. Introduction

On May 12, 2008, a large and shallow earthquake with M_w 7.9 struck the Wenchuan region in Eastern Sichuan, China, as reported by the U.S. Geological Survey (USGS) (Fig. 1). The earthquake caused serious destruction and loss of life and was the most severe earthquake in China since the 1976 M_s 7.6 Tangshan earthquake. The results of the field survey show that the 2008 Wenchuan earthquake occurred along the Longmenshan fault zone (a thrust-type and northwestward dipping fault) located at the border between the eastern Tibetan plateau and the Sichuan basin. They also suggest that the surface rupture is approximately 200–235 km long, terminating around Shikan (Fig. 1) (Liu-Zeng *et al.*, 2009; Xu *et al.*, 2009a; Li *et al.*, 2010), while the aftershocks have a northeastward distribution extending approximately 300 km from the epicenter (Fig. 1), consistent with the results of the survey based on InSAR information (Hao *et al.*, 2009). Previous studies of the 2008 Wenchuan earthquake revealed a rupture length of approximately 230–300 km and a source duration of approximately 70–120 s, with the largest rupture occurring within 100 km of the epicenter (Chen *et al.*, 2008; Hikima, 2008; Ji and Hayes, 2008; Nishimura and Yagi, 2008; Sladen, 2008; Du *et al.*, 2009; Hao *et al.*, 2009; Shen *et al.*, 2009; Xu *et al.*, 2009b; Hashimoto *et al.*, 2010; Nakamura *et al.*, 2010; Zhao *et al.*, 2010). While the source rupture model from Nishimura and Yagi (2008), Shen *et al.* (2009), Sladen (2008), Wang *et al.* (2008), and Zhao *et al.* (2010) showed that this earthquake tore the surface, the source model from Ji and Hayes (2008), Hikima (2008), and Nakamura *et al.* (2010) did not reveal a surface rupture. However, all source models demonstrate that the main energy release is concentrated mostly within 30 km along the dipping-direction from the surface (depth about 20 km). The studies divided the faulting mechanism of the 2008 Wenchuan earthquake into two types: (1) thrusting in the earlier rupture; (2) strike-slip faulting in the later one (e.g., Hwang *et al.*, 2010). Wang *et al.* (2010) calculated co-seismic displacements of the source area from several source rupture models and suggested that the source model of Wang *et al.* (2008) is the best in terms of fitting GPS data.

A large earthquake due to long faulting and extension typically causes variations in seismic-wave duration and amplitude with the station azimuth; this is referred to as rupture directivity. Ben-Menahem (1961) first proposed the finite moving source theory to account for the effect of rupture propagation (i.e., source finiteness) on far-field seismograms, such as the Doppler effect. Source finiteness results in a time delay in surface-wave propagation and a number of

doi:10.5047/eps.2011.01.002

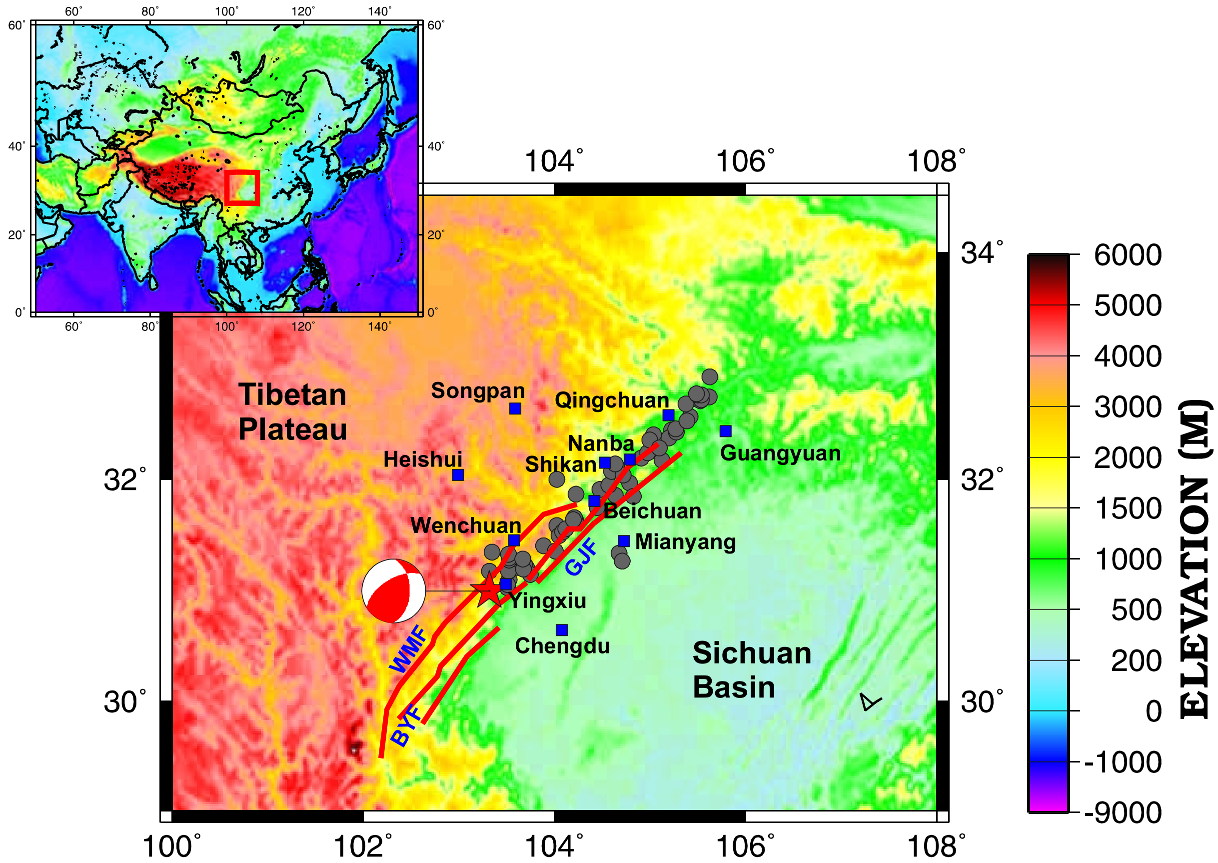

Fig. 1. Map showing the topography of the source area (topographic data from the NGDC, National Geophysical Data Center) for the 2008 Wenchuan earthquake. Star and circles denote the epicenter and aftershocks ($m_b \geq 5.0$), respectively. Also shown is the focal mechanism from the USGS. Close squares are several cities around the source area. Red lines denote three faults in the Longmenshan fault zone (WMF: Wenchuan-Maowen fault; BYF: Beichuan-Yingxiu fault; GJF: Guanxian-Jiangyou fault, also called the Pengguan fault).

nodes in the Fourier spectra (Ben-Menahem, 1961; Hwang *et al.*, 2001; Aki and Richards, 2002; Chang *et al.*, 2010). In the study reported here, we have estimated the azimuth-dependent phase-delay time of Rayleigh waves (i.e., source duration variation with azimuth) due to source rupture directivity during the 2008 Wenchuan earthquake (cf. Chang, 2009). Subsequently, this work combines the phase-delay time and spectral-node periods of Rayleigh waves to determine the fault parameters of the 2008 Wenchuan earthquake based on the finite moving source theory and to reveal its first-order rupture feature.

2. Data and Phase-Velocity Measurements

Long-period Rayleigh waves generated by the 2008 Wenchuan earthquake were extracted from vertical-component seismograms provided by the IRIS Data Management Center. Only seismic data with good Rayleigh-wave energy excitation and epicentral distances ranging from 30° to 90° were used in this study to measure the phase-velocity along the great-circle path. Prior to performing the phase-velocity measurements, we removed the instrumental response from each seismogram.

The phase velocity of the Rayleigh wave along the great-circle path from the earthquake to the station was derived by the single-station method (cf., Hwang and Yu, 2005; Chang *et al.*, 2007; Chang *et al.*, 2010). Hence, the time it takes for the Rayleigh wave to travel from a source to a given station at period T can be written as follows.

$$t(T) = \frac{L}{C(T)} = [\phi_{SR}(T) - \phi_{0R}(T) \pm N]\,T \qquad (1)$$

where $C(T)$ and $t(T)$ denote the phase-velocity and the corresponding travel time of a Rayleigh wave at a given period T, respectively; L is the epicentral distance; $\phi_{SR}(T)$ is the station phase after removing the instrumental response; $\phi_{0R}(T)$ is the initial phase of the source, calculated from a known focal mechanism and the velocity structure of the source area; N is an arbitrary integer for detecting the reasonable phase-velocities in the long-period part (cf., Chang *et al.*, 2007; Chang *et al.*, 2010). Here, the focal mechanism (strike/dip/rake = 231°/35°/138°) from the Global CMT is used to calculate the initial phase of the source. Figure 2 shows the 74 stations used in this study and the Rayleigh-wave travel-time for several stations. To avoid the influence of strong lateral variations in the shallow structure on the phase-velocity measurement for short-period surface waves as well as the uncertainty of estimated phase-velocity of long-period surface waves due to relatively smaller amplitude, we adopted only the 100-s phase-velocity of the Rayleigh wave in this study. We collected 69 travel-times and 28 periods of spectral-node used from the available stations, as shown in Fig. 3.

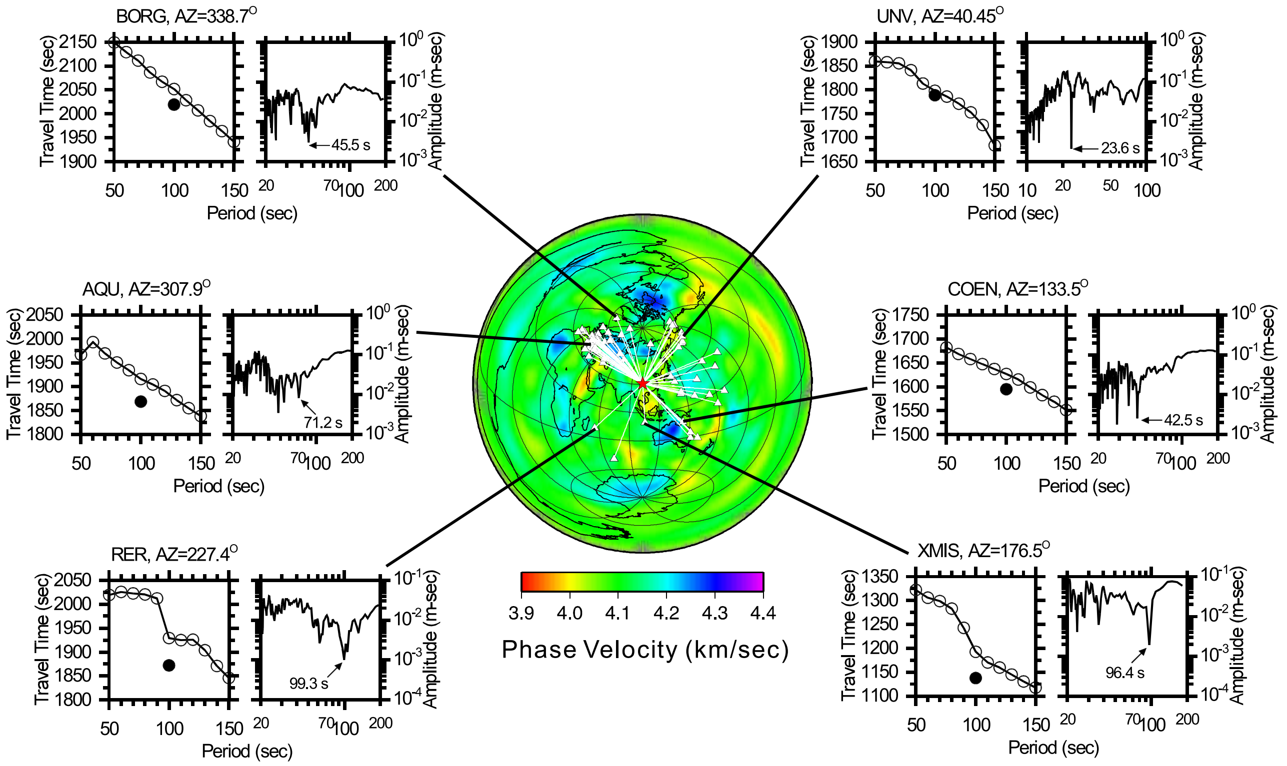

Fig. 2. The middle diagram is the global map of the Rayleigh-wave phase-velocity at a period of 100 s (Trampert and Woodhouse, 2001). Triangles denote the used stations in this study. Also included are travel-times (open circles) and the Fourier spectrum from several stations. Closed circles are the travel-times of the 100-s Rayleigh wave calculated from the global map of 100-s Rayleigh-wave phase-velocity. Numbers within the diagram of the Fourier spectrum denote the spectral-node period.

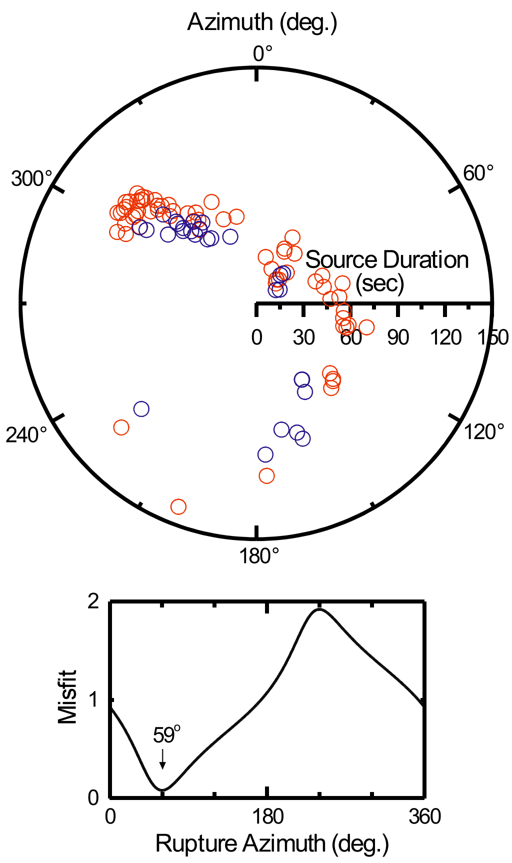

Fig. 3. (Upper) Apparent source duration (red circles) and the period of spectral-node (blue circles) varies with station azimuth. (Lower) The estimation of rupture direction denotes the best azimuth of $\sim 59^{\circ}$, measured clockwise from the north at 1°-interval searching.

3. Rupture Directivity Analysis

The travel-time for surface-wave propagation from a source to a station includes two phase-delay times: one from the source, including the rupture directivity (i.e., finite faulting) and initial phase; the other from the path effect due to propagation from the source through the Earth's structure to the station. To extract information on the source rupture directivity (i.e., variation of source duration with azimuth), we first eliminate the initial phase and path effect. Equation (1) shows the initial phase to be removed from the phase-velocity measurement. Taking into account the path effect due to the Earth's structure, this study calculates the theoretical Rayleigh wave travel-time (t_{cal}) from the source to the station through a known global surface-wave phase-velocity map derived by Trampert and Woodhouse (2001) (also see Fig. 2 and Appendix A). Therefore, the apparent variation in the source duration ($T_{\mathrm{SPT}}(\Theta)$) with the station azimuth is equal to $2 \times (t_{\mathrm{obs}} - t_{\mathrm{cal}})$, where t_{obs} and t_{cal} are observed and theoretical Rayleigh-wave travel-time, respectively (Chang, 2009). Figure 3 shows the variation in apparent source duration with azimuth, which fulfills the feature of unilateral rupture (cf. Chang, 2009; Chang et al., 2010). Hence, for a unilateral faulting event, $T_{\mathrm{SPT}}(\Theta)$ can be expressed as (e.g., Hwang et al., 2001; Chang, 2009; Chang et al., 2010):

$$T_{\mathrm{SPT}}(\Theta) = 2 \times (t_{\mathrm{obs}} - t_{\mathrm{cal}}) = \left(\frac{L}{V_{\mathrm{r}}} - \frac{L}{C}\cos\Theta\right) + \tau = \left(\frac{L}{V_{\mathrm{r}}} + \tau\right) - \frac{L}{C}\cos\Theta \qquad (2)$$

where τ is the rise time; L is the rupture length; V_{r} is the rupture velocity; C is the phase velocity in the source region as a function of period; $\Theta = \phi_{\mathrm{s}} - \phi_{\mathrm{f}}$ is the angle between the station azimuth (ϕ_{s}) and the direction of the fault rupturing (ϕ_{f}). Using a standard linear regression, in this study we estimate L/C and $(L/V_{\mathrm{r}} + \tau)$ and then determine several fault parameters, including the source duration (i.e., $L/V_{\mathrm{r}} + \tau$), rupture length, rupture velocity, and rupture azimuth. For details about the rupture directivity analysis mentioned above, refer to Hwang et al. (2001), Chang (2009), and Chang et al. (2010). Figure 2 shows the calculated 100-s travel-time of the Rayleigh wave based on the model of Trampert and Woodhouse (2001). Multiple event analysis (Hwang et al., 2010) shows seven sub-events with M_{w} of 7.0, 6.5, 7.5, 7.4, 7.2, 7.4, and 7.2 in order along the rupturing zone. Then, overall, the 2008 Wenchuan earthquake can be regarded more or less as an event with uniform rupturing in terms of surface-wave observations, particularly long-period surface waves. Hence, the use of equations is a feasible approach to analyze the first-order rupture feature of the 2008 Wenchuan earthquake.

The rupture directivity of the finite source not only makes the phase-velocity of the Rayleigh wave slow, but it also weakens the amplitude spectra of the Rayleigh wave by the absolute value of a sinc function, $\frac{\sin X}{X}$, with $X = \frac{\omega}{2}\left(\frac{L}{V_{\mathrm{r}}} - \frac{L}{C}\cos\Theta\right)$, where ω is the angular frequency, and the other parameters are the same as those in Eq. (2). The sinc function produces spectral nodes at $X = n\pi$, i.e., at periods $T_n = \frac{1}{n}\left(\frac{L}{V_{\mathrm{r}}} - \frac{L}{C}\cos\Theta\right)$, where n is the node number ($n = 1, 2, 3, ...$) (also refer to chapter 10 of Aki and Richards, 2002; Chang, 2009; Chang et al., 2010). Hence, the apparent source duration (nT_n) due to the rupture directivity from the spectral-node periods can be written as,

$$nT_n = \frac{L}{V_{\mathrm{r}}} - \frac{L}{C}\cos\Theta \qquad (3)$$

Note that Eq. (3) excludes the rise time from the apparent source duration. C is also a function of period, as in Eq. (2). In theory, Eqs. (2) and (3) have the same slopes (L/C and L/V_{r}). A comparison of Eqs. (2) and (3) gives the rise time, as in Hwang et al. (2001) and Chang et al. (2010). Here, we used a matrix form to simultaneously solve L/C, L/V_{r}, and τ by a standard least-squares technique, as in the following form.

$$\begin{bmatrix} 1 & \cos\Theta & 1 \\ 1 & \cos\Theta & 0 \end{bmatrix} \begin{bmatrix} \frac{L}{V_{\mathrm{r}}} \\ -\frac{L}{C} \\ \tau \end{bmatrix} = \begin{bmatrix} T_{\mathrm{SPT}} \\ nT_n \end{bmatrix} \qquad (4)$$

Because the phase-velocity (C) in Eq. (3) is also a function of period, it is difficult to perform the joint inversion with Eq. (4) only using a 100-s phase-velocity of the Rayleigh wave. It is known that the rise time is azimuth independent and not a function of period. Under the same C, the apparent source duration estimated from travel-time is larger than that estimated from the period of spectral-node; the difference in time between the two apparent source duration is then the rise time (see Eqs. (2) and (3)). The distribution of aftershocks and fault plane solution (from the USGS and GCMT) showed possible rupture azimuth, $\sim 60^\circ$. In order to make the observed source duration independent of azimuth and period (i.e., average source duration), we first selected the stations located at the azimuth around $\sim 150^\circ$ or $\sim 330^\circ$, perpendicular to the rupture direction, in order to remove $\cos\Theta$ from Eqs. (2) and (3). The apparent source duration observed at the azimuth around $\sim 150^\circ$ or $\sim 330^\circ$ is approximately 60–70 s, which can be regarded as the average source duration. Following Geller (1976), the rise time is about 10–20% of the average source duration. That is, the rise time is probably 6–14 s. In fact, in this study, spectral-nodes observed at stations with an azimuth around $\sim 150^\circ$ are absent, so only those observed at a station azimuth of around $\sim 330^\circ$ are used. For stations with an azimuth around $\sim 330^\circ$, we picked out the period of the first spectral-node that was less than the apparent source duration estimated from the travel-time by 7–14 s, averaging ~ 10 s, adhering to Geller's suggestions. In other words, the difference in time between the two apparent source durations (estimated from travel-time and spectral-node period, respectively) for the rest of stations should also be around ~ 10 s since the rise time is independent of both azimuth and period. This gives us information for assessing the spectral-node period. Hence, in order to make Eq. (4) available only using the 100-s phase-velocity of Rayleigh-wave, we have to apply the following criteria in choosing the applicable spectral-node period for a given station: (1) the apparent source duration estimated from spectral-node period (nT_n) is less than that estimated from Rayleigh-wave travel-time ($T_{\rm SPT}$), i.e., $nT_n < T_{\rm SPT}$; (2) ($T_{\rm SPT} - nT_n$) is around ~10 s.

The first term in the left-hand side of Eq. (4) is the so-called kernel matrix, which can be used to construct a covariance matrix ($C_{\rm o}$). The standard deviations for those unknown parameters (L/C, $L/V_{\rm r}$ and τ) are then calculated as (Ewing and Mitchell, 1970):

$$\sigma_i = \left[\frac{\varepsilon^2}{m-k} C_{{\rm o}ii}\right]^{1/2}$$

where m is the number of observed data, k is the number of unknown parameters, and σ_i is the standard deviation of the ith parameter. ε^2 is the error sum of squares between the observed and predicated data. $C_{{\rm o}ii}$ is the ith diagonal element of the covariance matrix.

4. Results

Figure 3 shows the source duration estimated from the 100-s Rayleigh wave at various station azimuths (red circles) and that estimated from the first spectral-node period (blue circles). The red circles in Fig. 3 show that the maximum apparent source duration is ~140 s, observed in an azimuth of about 200°, whereas the minimum apparent source duration is ~20 s, observed in an azimuth of about 33°. Hence, Fig. 3 obviously indicates that the 2008 Wenchuan earthquake is an event with unilateral faulting and northeastward ruptures. Following sorting of a series of rupture azimuths through Eq. (4), the optimal rupture azimuth is about 59°, measured clockwise from the north (bottom of Fig. 3). Meanwhile, we obtain a rise time of approximately 9.3±0.6 s, a rupture time of approximately 60.7±0.5 s, and a propagation time of approximately 50.5±0.5 s (time for 100-s Rayleigh wave passing through the fault). Hence, the entire source duration is 70.0±0.8 s, i.e., the rupture time plus the rise time. When the phase-velocity in the source area is taken to be 4.15 km/s at 100 s from Trampert and Woodhouse (2001), we estimate the rupture length from the propagation time to be 209.6±2.1 km. The rupture velocity estimated from the entire source duration is about 3.0±0.1 km/s, whereas the rupture velocity estimated only from the rupture time is then about 3.45±0.1 km/s. Figure 4 shows that the theoretical source duration calculated from the estimated parameters (Table 1) using Eq. (2) explains well the observed source duration.

Following Mai and Beroza (2000), the efficient width (w) of the fault is about 0.77-fold as large as the width of the source rupture model. Hence, from the source model of Ji and Hayes (2008), the efficient width of the fault for the 2008 Wenchuan earthquake is about 30.8 km. Using $M_0 = \mu AD$ and taking $M_0 = 7.6 \times 10^{20}$ N m (seismic moment from the USGS), $\mu = 2.76 \times 10^{10}$ N m^{-2} (the rigidity in the source area using $\mu = \rho\beta^2$ with $\rho = 2.45$ g/cm^3 and $\beta = 3.36$ km/s) and $A = 209.6 \times 30.8$ km^2 (the area of the fault), the average dislocation (D) is then about 4.27 m. Since this study estimates the rise time to be 9.3 s, the average particle velocity ($\dot{D}$) is about 46±2.8 cm/s. For this reason, we determine the average dynamic stress drop to be about 37.8±2.3 bars following Brune (1970), using $\Delta\sigma_{\rm d} = \mu\frac{\dot{D}}{\beta}$ (the average S-wave velocity $\beta = 3.36$ km/s in the source area within a 20-km depth of the crust following Pei *et al.* (2010)). Given that the 2008 Wenchuan earthquake did break the surface (cf. Nishimura and Yagi, 2008; Sladen, 2008; Wang *et al.*, 2008; Shen *et al.*, 2009; Zhao *et al.*, 2010), we estimate the static stress drop to be 32.5 bars using $\Delta\sigma_{\rm s} = \frac{4(\lambda+\mu)}{\pi(\lambda+2\mu)}\mu\frac{D}{w}$ when taking $\lambda = \mu$ and $w = 30.8$ km. An estimate of the radiated seismic energy ($E_{\rm S}$), according to $E_{\rm S} = \frac{M_0}{2\mu}(2\Delta\sigma_{\rm d} - \Delta\sigma_{\rm s})$ (Kanamori and Heaton, 2000), is $(5.93 \pm 0.4) \times 10^{16}$ N m; moreover, the $E_{\rm S}/M_0$ ratio is $(7.8\pm0.5)\times10^{-5}$. Table 1 lists these estimated fault parameters of the 2008 Wenchuan earthquake.

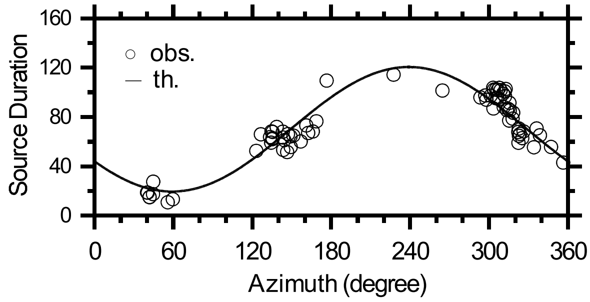

Fig. 4. Comparisons of the observed (circles) and theoretical (solid lines) source duration. The observed source duration is estimated from the travel time of the 100-s Rayleigh wave. The theoretical source duration is calculated from the estimated parameters (Table 1) using Eq. (2).

Table 1. Fault parameters estimated in this study.

Rupture length	209.6±2.1 km
Source duration	70.0±0.8 s
Rupture azimuth	59°
Rupture time	60.7±0.5 s
Rise time	9.3±0.6 s
Rupture velocity[1]	3.00±0.1 km/s
Rupture velocity[2]	3.45±0.1 km/s
Particle velocity	46±2.8 cm/s
Static stress drop	32.5 bars
Dynamic stress drop	37.8±2.3 bars
Radiated seismic energy	$(5.93 \pm 0.4) \times 10^{16}$ N m

[1]The rupture velocity is estimated from the entire source duration.
[2]The rupture velocity is estimated only from the rupture time.

5. Discussion and Conclusions

A steep variation in travel-time was observed at stations RER and XMIS, particularly for RER (Fig. 2). Because these stations are approximately located at the opposite direction of faulting, the rupture directivity reduces significantly the observed amplitude of Rayleigh wave to make it difficult to measure phase-velocity due to the problem of phase-skip, especially for the short-period surface waves. We also derived the fault parameters from the 60-s Rayleigh wave; these show high consistencies with those derived from the 100-s Rayleigh wave, but appear to underestimate slightly the fault parameters when using short-period surface waves. Furthermore, Chang (2009) found that it is better to use the 100-s period surface wave in analyzing the fault parameters for large earthquakes with $M_{\rm w}$ 7.5–8.5.

Several groups have reported the fault plane solution for the 2008 Wenchuan earthquake using as the best double couple either 238°/59°/128° and 2°/47°/45° (strike/dip/rake) from the UGGS or 231°/35°/138° and 357°/68°/63° from the Global CMT. Our study measures the optimal rupture azimuth at 59° in the clockwise direction from the north, and the results indicate that the earthquake ruptured northeastward and that its fault plane is 238°/59°/128° (from the USGS) or 231°/35°/138° (from the Global CMT), with a NW-dipping plane. This feature is consistent with the geological survey (cf. Xu *et al.*, 2009a) and the aftershock distribution (see Fig. 1).

The estimated source duration and rupture length are 70.0 s and ∼210 km (see Table 1), which are relatively shorter than those reported from source rupture models (e.g., Hikima, 2008; Ji and Hayes, 2008; Nishimura and Yagi, 2008; Hao *et al.*, 2009; Nakamura *et al.*, 2010). However, our estimates also agree with a source rupture model reported initially in the article of Chen *et al.* (2008) and the multiple event analysis of Hwang *et al.* (2010). Following Mai and Beroza (2000), the efficient rupture length of the fault for the 2008 Wenchuan earthquake is ∼240 km from the source model of Ji and Hayes (2008), and ∼190 km from that of Sladen (2008). Spatial distribution of the *b*-value (Zhao and Wu, 2008) also showed relatively low *b*-values (∼0.5–0.7) in most northeast segments of the fault, implying relatively small slips there (e.g., Wiemer and Katsumata, 1999). This probably indicates that the rupture length is shorter from the *b*-value map (∼250 km) than that from the aftershock distribution. In addition to those characteristics mentioned above, slip distribution estimated from GPS and InSAR data revealed three maxima in slip near the towns of Yingxiu, Beichuan, and Nanba (Shen *et al.*, 2009; also see Fig. 1). Wang *et al.* (2008) and Xu *et al.* (2009b) obtained similar results, and indicated a relatively low energy release (<30% of total energy releases) to the Qingchuan town (see Fig. 1). Since the surface waves mainly detect large energy releases, the rupture length from the epicenter to the Nanba town, according to the source models of Shen *et al.* (2009), Xu *et al.* (2009b), and Wang *et al.* (2008), is approximately 220–230 km. Furthermore, an empirical formula of seismic moment versus source duration (Furumoto and Nakanishi, 1983) suggested a source duration of 67 s for $M_0 = 7.6 \times 10^{20}$ N m (from the USGS) or a source duration of 71 s for $M_0 = 8.97 \times 10^{20}$ N m (from the Global CMT), with which our estimated source duration is in good agreement. Concerning the relationship between seismic moment and the fault area (cf. Kanamori and Anderson, 1975), the fault's area is ∼7254 km^2 for $M_0 = 7.6 \times 10^{20}$ N m, leading to the rupture length of ∼235 km when the fault's width is taken to be ∼30.8 km. As addressed above, our estimates account for 70% of the energy released during the 2008 Wenchuan earthquake from surface-wave analyses (cf. Xu *et al.*, 2009b). In other words, our estimations are probably the lower bound of the rupture process, revealing the first-order rupture features for the 2008 Wenchuan earthquake, namely, the main energy release process.

The rise time for earthquakes is an important parameter related to the dynamic stress drop during earthquake faulting. The entire source duration includes the rise time and the rupture time. Because the rise time is shorter relative to the entire source duration, it is not easily separated from the entire source duration. Generally, the rise time is about 10–20% of the entire source duration (cf. Geller, 1976). However, simultaneous use of the phase-delay time and the Fourier spectral node period of surface waves are capable of solving the rise time from the entire source duration. Hwang *et al.* (2001) and Chang *et al.* (2010) have done such work. Equation (4) shows that by sorting a series of rupture azimuths, the rise time for the 2008 Wenchuan earthquake can be determined to be 9.3 s, which is ∼0.13-fold the value of the entire source duration. This leads to a particle velocity of 46 cm/s and a dynamic stress drop of 37.8 bars, corresponding to the observations for large earthquakes (Kanamori, 1994).

The rupture velocity estimated from the entire source duration is ∼3.0 km/s, which agrees well with the average one from Nishimura and Yagi (2008) and Zhang *et al.* (2009). However, the rupture velocity determined only from the rupture time is ∼3.45 km/s, probably exceeding the S-wave velocity in the crust. This is in accordance with the estimation (∼3.4 km/s) of Du *et al.* (2009) from teleseismic array analysis. Of course, variable S-wave velocities lead to various rupture features during earthquake faulting, i.e., subsonic, sonic, and supersonic faulting. A three-dimensional velocity structure derived by Pei *et al.* (2010) indicates that the velocity of the S-wave velocity across the source area within the crust ranges from 3.25 to 3.5 km/s. In other words, the estimated rupture velocity might exceed or be close to the S-wave velocity. This is quite different from other thrust-type earthquakes, for instance the 1999 Chi-Chi earthquake and the 2004 great Sumatra earthquake (cf. Hwang *et al.*, 2001; Chang *et al.*, 2010). Nevertheless, previous studies have reported strike-slip earthquakes with a relatively larger rupture velocity, such as the 2001 Kunlun (China) earthquake and the 2002 Denali fault (Alaska) earthquake (cf. Walker and Shearer, 2009; Wen *et al.*, 2009). Multiple event analysis and the source rupture model for the 2008 Wenchuan earthquake suggest that ruptures in the former segment of the fault exhibit a thrust-type mechanism while those in the later one show a strike-slip mechanism (cf. Ji and Hayes, 2008; Nishimura and Yagi, 2008; Sladen, 2008; Zhang *et al.*, 2009; Hashimoto *et al.*, 2010; Hwang *et al.*, 2010; Nakamura *et al.*, 2010; Zhao *et al.*, 2010). The rupture process of the 2008 Wenchuan earthquake with a strike-slip-type in the later portion of the fault might result in higher average rupture velocity.

Since rupture velocity is high; once fracture energy is ignored (cf. Kanamori and Heaton, 2000), the radiated seismic energy can be estimated to be $(5.93 \pm 0.4) \times 10^{16}$ N m based on the static and dynamic stresses according to Kanamori and Heaton (2000). Although this value is larger than that from the routine report of the USGS (1.4×10^{16} N m), both sets of results have the same order of magnitude. Our estimate also agrees with that from multiple event analysis of Hwang *et al.* (2010). Moreover, the E_S/M_0 ratio, approximately $(7.8 \pm 0.5) \times 10^{-5}$ is quite close to global observations (approx. 5.0×10^{-5}) (cf. Kanamori and Heaton, 2000). From the rupture directivity analysis based on the Rayleigh-wave phase-velocity and its Fourier spectrum, we were able to efficiently estimate the fault parameters for the 2008 Wenchuan earthquake, showing a unilateral faulting event.

Acknowledgments. The authors would like to express their gratitude to the IRIS (Incorporated Research Institutes for Seismology) for providing us with the GSN data. We offer a special thanks to Dr. Kazunori Yoshizawa and an anonymous reviewer, who have helped us significantly improve the manuscript. The National Science Council, ROC, financially supported this study under Grant Nos. NSC98-2119-M-034-001, NSC98-2811-M-034-002, and NSC99-2116-M-034-003.

Appendix A.

Following Trampert and Woodhouse (1995, 2001) and Zhang and Lay (1996), the travel-time anomaly (Δt) from the source to the station along the great-circle path can be written as:

$$\Delta t = -\frac{1}{v_0}\int_{\text{path}} \frac{\Delta v(\theta,\phi)}{v_0} ds \tag{A.1}$$

where v_0 is the reference phase-velocity calculated from the PREM model (Dziewonski and Anderson, 1981), and Δv is the phase-velocity perturbation relative to v_0 at position (θ, ϕ) where θ is co-latitude and ϕ is longitude.

In Eq. (A.1), $\frac{\Delta v(\theta,\phi)}{v_0}$ is expanded in spherical harmonics with degrees up to 40 as follows.

$$\frac{\Delta v(\theta,\phi)}{v_0} = \sum_{l=0}^{40}\sum_{m=0}^{l}\left[a_{lm}\cos(m\phi) + b_{lm}\sin(m\phi)\right] P_l^m(\theta) \tag{A.2}$$

where a_{lm} and b_{lm} are coefficients of spherical harmonic functions, and the spherical harmonics are fully normalized with

$$P_l^m(\theta) = \left[(2-\delta_{m,0})(2l+1)\frac{(l-m)!}{(l+m)!}\right]^{1/2} p_l^m(\cos\theta)$$

where $p_l^m(\cos\theta)$ are the associated Legendre polynomials, and $\delta_{m,0} = 1$ for $m = 0$ and $\delta_{m,0} = 0$ for $m \neq 0$.

Trampert and Woodhouse (2001) provided the coefficients of a_{lm} and b_{lm} to make it possible to calculate the theoretical travel-time (t_{cal}) of a surface-wave from point to point in the following form.

$$t_{\text{cal}} = t_0 + \Delta t \tag{A.3}$$

where t_0 is the average travel-time of the surface-wave based on the PREM model and Δt is the travel-time anomaly estimated by the path integral in Eq. (A.1) using known coefficients of spherical harmonic functions. The calculated travel-time (t_{cal}) is independent of the finite-source.

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