Large slip rate detected at the seismogenic zone of the 2008 M_W 7.9 Wenchuan earthquake*

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Abstract Repeating microearthquakes were identified along the edge of the rupture area of the 2008 M_W 7.9 Wenchuan earthquake. Slip rates at depths derived from seismic moments and recurrence intervals are found to be systematically larger than those observed at surface. This large deep slip rate may explain the odds about the occurrence of this unanticipated event. Our observations here suggested that seismic hazard could be underestimated if surface measurements alone are employed.

Key words: deep slip rate; repeating microearthquake; Wenchuan earthquake

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1 Introduction

The 2008 M_W 7.9 Wenchuan, China, earthquake ruptured the northern segment of the ~ 400 km Longmenshan fault zone (LMSFZ) extending from Luding to Qingchuan at the eastern margin of the Tibetan Plateau (Burchfiel et al., 2008; Xu et al., 2009). Seismicity along this seismic zone is generally restricted to small events ($M < 5$) that occur in a ~ 70 km wide band along the margin featured by large topographic relief. Prior to the Wenchuan earthquake, the Longmenshan thrust belt had been seismically quiet for several centuries, there was no earthquake with $M > 7$ documented in any historical records (State Seismological Bureau, 1995). Geological (Tang and Han, 1993; Densmore et al., 2007) and geodetic (Chen et al., 2000; Zhang et al., 2004; Shen et al., 2005) data also indicate little to no active convergence, with a slip rate < 3 mm/a across the LMSFZ. The limited seismic activity and low deformation rate had led to a modest estimate of strain accumulation and seismic hazard of this area (Group of *Research on Earthquake Risk Regions and Losses Prediction of China Continent from 2006 to*

2020, 2007). While geodesy provides important constraints on the surface strain field, geodetic observations made at Earth's surface, however, have very limited ability in detecting deformation (Bos and Spakman, 2003) and other fault zone processes such as fluid redistribution (Taira et al., 2009) occurring at seismogenic depths. The low deformation rate observed at the surface of LMSFZ thus may not necessarily reflect the slip rate at depth where the devastating earthquake nucleated.

Surface constraints need to be combined with other techniques that, while not as directly related to strain, have superior depth resolution. The most promising techniques at present appear to be seismic (Niu et al., 2003). The discovery of characteristic repeating earthquake sequences offered a new way to estimate in-situ slip rates throughout the surface of an active fault (Nadeau and Johnson, 1998; Nadeau and McEvilly, 1999). Repeating earthquakes are a series of earthquakes regularly occurring on a patch of a fault plane. These earthquakes usually have approximately the same magnitude with roughly the same repeating interval, and produce nearly identical seismograms when recorded at the same station. They are commonly interpreted as repeated ruptures of a single asperity surrounded by a weak and creeping area. Creeping rates thus can be estimated from coseismic slips that are calculated from the released seismic moments and recurrence

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intervals of the sequences (Nadeau and Johnson, 1998; Nadeau and McEvilly, 1999). They have been combined with geodetic measurements to determine tectonic loading rate of faults (Bürgmann et al., 2000). Repeating earthquakes have been observed at various tectonic environments such as the San Andreas fault system (Nadeau and Johnson, 1998; Nadeau and McEvilly, 1999), subducting slab interface in northeastern Japan (Igarashi et al., 2003), the northern Anatolian fault (Peng and Ben-Zion, 2006), the Taiwan arc-continent collision boundary (Rau et al., 2007; Chen et al., 2008), and the fault of the 1976 $M_{7.8}$ Tangshan earthquake (Li et al., 2007). Schaff and Richards (2004) found that about 10% of the seismic events in China were repeating earthquakes.

2 Data and analysis

We analyzed waveform data recorded by a regional seismic network (29 stations) under the China Earthquake Administration and a local seismic network (seven stations) for reservoir monitoring near the epicenter to search for repeating earthquakes and to estimate slip rates along the LMSFZ (Figure 1). The two networks recorded a total of 5 246 micro-earthquakes ($0.1 \leq M_L \leq 4.2$) occurring along the LMSFZ between May 2000 and April 2008. We started the search by looking for events that show similar waveforms registered at each station using a cross-correlation technique. Waveform data were first filtered between 1 Hz and 10 Hz and then interpolated to a higher sampling rate

Figure 1 Geographic map of the Longmenshan and western Sichuan Basin. The epicenter (white dot) and focal mechanism of the 2008 $M_{7.9}$ Wenchuan earthquake are shown together with the three major faults that make up the Longmenshan fault zone. The regional seismic network of the China Earthquake Administration and local seismic network for reservoir monitoring are shown by red and orange triangles, respectively. Inset in the right bottom corner shows surface motion (in unit of mm/a) of the Indian Plate and different blocks within the Tibetan Plateau relative to the stable Siberian Craton. Inset in the upper left corner shows a schematic cross section of the Longmenshan fault zone. Dot indicates the hypocenter of the $M_{7.9}$ earthquake.

(Li et al., 2007). Cross-correlation coefficient C_C was computed with a time window 1 s before P and 5 s after S among all possible pairs of earthquakes recorded at each station. We found a total of 455 similar event sequences with a $C_C > 0.80$, which comprised 231 doublets and 224 multiplets that have 2 to 180 event members. Figure 2a shows an example of seismograms of an identified repeating sequence. The total number of earthquakes in the 455 sequences is 2419, making up about 46% of the entire seismicity. Most of the sequences showed substantial variations in both the recurrence

interval and event magnitude. It is likely that many sequences here included earthquakes that are close but still displaced from each other with no to little overlap in rupture area.

To better determine relative location among earthquakes in a sequence, we first construct a reference seismogram for each multiplet, which can be considered as the seismogram as if an event occurred at the centroid of the multiplet. We then measured the arrival times of the P and S waves relative to the reference seismogram for each sequence. To ensure the accuracy in measuring

Figure 2 (a) An example of seismograms from the sequence S05 recorded at the YZP station. Each trace was normalized by its maximum amplitude. The lowest panel shows the overlap of all the seismograms. (b) Map view of the relative locations of the 13 events in the S05 multiplet. Three events (#4, #6, #9) have little to no overlap with the other events, and were therefore eliminated from the repeating earthquake sequence. (c) Cumulative slips calculated from the repeating earthquake sequence S05, which has 10 events. Event 1 occurs at time zero and is not shown here.

the arrival time, we only selected multiplets with an average $C_C > 0.90$. We used both signal-to-noise ratio and internal consistence to estimate errors in travel-time measurements, and kept the errors to be less than 0.5 ms. Finally, we applied the fine relocation method (Got et al., 1994; Cheng et al., 2007) to the measured relative times to obtain the location of each event relative to the sequence centroid (Figure 2b). In computing the rupture area, we converted the local magnitude to seismic moment and assumed a circular model with a coseismic stress drop of 3 MPa (Kanamori and Anderson, 1975; Hanks and Kanamori, 1979; Li et al., 2007). Based on the relative distances and rupture sizes, we identified a total of 11 sequences as repeating clusters (Table 1). We assumed that coseismic slips were built up during the recurrence interval and estimated the slip rate by a linear regression to fit the accumulated slip during the entire sequence period (Table 1). Slip rate estimated from the 11 sequences varies from 2.9 mm/a

to 7.9 mm/a with an average of 5.1 mm/a, and is approximately twice as large as the surface observations.

Catalog locations were routinely determined from picks of P- and S-wave arrival times with a 1D two-layered velocity model. Typical location error is in the order of a few kilometers to a couple tens of kilometers. To better constrain the 11 sequences along the LMSFZ, we relocated the 3D seismicity using the double difference method (Waldhauser and Ellsworth, 2000) with a refined velocity model. The model is based on a recent tomographic study of the region (Huang et al., 2008) and consists of two different 1D velocity structure corresponding to the Tibetan Plateau and Sichuan Basin located at the two sides of the LMSFZ. We manually confirmed the entire catalog picks and incorporated a significant amount of picks with cross-correlation based differential travel times. The 11 sequences cover the entire depth range of the LMSFZ (Table 1, Figure 3). Seven of the 11 sequences are located beneath the Wenchuan

Table 1 Repeating earthquake sequences identified along the Longmenshan fault zone

No.	N	Sequence centroid location			M_L	T_r/a	Slip rate ($\text{mm}\cdot\text{a}^{-1}$)	Accumulated slip/mm	Sequence duration/a
		Long./°E	Lat./°N	Depth/km					
S01	5	103.254 5	30.905 7	6.2	1.3–2.1	0.08–1.48	4.0 ± 1.1	14.0	2.76
S02	8	103.303 7	31.192 7	13.1	1.4–2.8	0.01–1.81	5.3 ± 0.7	33.0	4.66
S03	5	103.635 5	31.187 0	4.0	1.5–1.9	0.10–0.70	5.8 ± 0.6	12.9	1.59
S04	7	103.674 1	31.186 2	16.0	1.2–2.0	0.02–1.07	6.0 ± 1.6	13.6	2.23
S05	10	103.763 2	31.177 9	14.3	1.3–2.8	0.08–2.28	5.4 ± 1.3	39.5	5.52
S06	6	103.717 7	31.221 2	17.3	1.6–1.9	0.02–1.11	6.8 ± 2.4	15.5	1.95
S07	5	103.800 6	31.299 6	10.5	1.4–2.0	0.07–1.33	4.5 ± 1.1	10.6	2.04
S08	10	104.433 5	31.776 5	9.5	1.2–2.2	0.06–1.60	7.9 ± 1.3	29.4	3.97
S09	9	104.454 9	31.760 4	4.3	0.9–1.8	1.00–1.66	2.9 ± 0.3	17.6	5.56
S10	5	104.446 4	31.823 8	4.6	1.4–1.8	0.45–1.76	4.0 ± 0.5	11.2	3.87
S11	3	105.146 1	32.080 8	6.7	1.9–2.3	0.13–1.13	3.2 ± 2.7	9.52	1.26

Note: N denotes number of earthquakes within each sequence, and T_r denotes recurrence interval.

Figure 3 Slip rates estimated from the 11 repeating earthquake sequences are shown in a depth section together with inverted coseismic slip of Ji and Hayes (2008). Amplitude of coseismic slip is shown on the right side of the map. Crosses indicate the locations of the 11 sequences with sizes proportional to the estimated slip rates in unit of mm/a.

area where the 2008 main shock started. The other four clusters are found beneath the Beichuan and Pingwu where large coseismic slips were also observed.

3 Discussion and conclusions

Most of the sequences are located at the edge of areas with large coseismic slip during the 2008 Wenchuan earthquake (Ji and Hayes, 2008) (Figure 3). These areas are known as asperities that are locked during the interseismic deformation given by the quick solution (Ji and Hayes, 2008) and recent study (Shen et al., 2009). Igarashi et al. (2003) found the same spatial correlation between repeating microearthquakes and asperities of major earthquakes at the northeastern Japan subduction zone. Mapping the spatial distribution of repeating earthquakes thus could provide a way to constrain rupture area for impending earthquakes. In general slip rates estimated from the deep clusters tend to be larger than those from the shallow ones. The highest slip rates are found at a depth range of 13 to 18 km. The observation of increasing slip rates with depth has significant implications in assessing risk of seismic hazard. Slip rates at seismogenic depths are of critical importance in estimating the recurrence of large earthquakes. The observation here may also provide constraints on the explanation of the development of Longmenshan thrust belt. The increasing slip rate with depth indicates that deep thrusting may also contribute to the strain accumulation along the LMSFZ besides the lateral compression. Dynamic pressure from lower-crustal flow (Royden et al., 1997; Hubbard and Shaw, 2009) could contribute to this deep thrusting.

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