Is the deformation rate of the Longmenshan fault zone really small? Insight from seismic data at the two-decade time scale

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Local earthquake catalogues complete down to M_L 2.5 are used to calculate the cumulative Benioff strain along the central- and north-Longmenshan fault zone which accommodated the May 12, 2008, Wenchuan M_S 8.0 earthquake. The nearby Xianshuihe, Anninghe, and Zemuhe fault zone are used for comparison. The data revealed that at the two-decade time scale which is different from geological process and GPS measurement, considering both horizontal and vertical deformation, and comparing with the neighboring active fault systems, the Longmenshan fault zone seems not as 'quiet' as traditionally assessed, providing a lesson for future seismic hazard analysis.

Key words: Wenchuan earthquake, Longmenshan fault zone, deep deformation, Benioff strain.

1. Introduction

One of the causes for the Longmenshan fault zone to be 'neglected' before the May 12, 2008, Wenchuan, M_S 8.0 earthquake was that geological evidences and GPS measurements all indicated that this fault zone is the one with extremely slow deformation rate (Burchfiel *et al.*, 2008; Zhang *et al.*, 2008). Tectonic studies indicate that the Longmenshan fault is characterized by its low slip rate, as concluded by Densmore *et al.* (2007) who estimated that the slip rate of the Yingxiu-Beichuan fault, a separate strand of the Longmenshan fault, is less than 0.5 mm/yr, and that of the Guanxian-Jiangyou fault, another separate strand, is about 0.6 mm/yr. Zhou *et al.* (2007) obtained that for the Longmenshan fault the strike-slip rate is less than 1.46 mm/yr and the thrust rate is less than 1.1 mm/yr. As a comparison, according to Xu *et al.* (2003, 2005), the neighboring Xianshuihe fault has the slip rate (14±2) mm/yr, the Anninghe fault has the slip rate (6.5±1) mm/yr, and the Zemuhe fault has the slip rate (6.4±0.6) mm/yr, more than 4 times of that of the Longmenshan fault. GPS observation gives that the crust shortening rate of the Longmenshan fault is 0∼5 mm/yr (King *et al.*, 1997), 1∼5 mm/yr (Holt *et al.*, 2000), less than 3 mm/yr (Chen *et al.*, 2000), less than 2 mm/yr (Wang *et al.*, 2003), or (4.0±2.0) mm/yr (Zhang *et al.*, 2004). As a comparison, according to Li *et al.* (2003), the Xianshuihe-Xiaojiang fault zone has the slip rate (9.8±2.2) mm/yr, being consistent with Wang *et al.* (2003) who obtained 9 mm/yr, more than 3 times of that of the Longmenshan fault zone. Zhang *et al.* (2008) concluded that the deformation rate of the Longmenshan fault has been very low for a long time—at the ten thousand year time scale it is less than 2 mm/yr. Moreover, Shen *et al.* (2003) and Jiang *et al.* (2003) used GPS results to calculate the shear strain rate of the Longmenshan fault zone, concluding that it is much less than that of the Xianshuihe, Anninghe, and Zemuhe fault zone. It is not surprising, therefore, that in the assessment of seismic hazard, the Longmenshan fault zone is to a great extent 'neglected'.

The occurrence of the May 12, 2008, Wenchuan earthquake reveals two important blind spots in our traditional understandings. The first is that the deformation rate as given by tectonic studies reflects the long-term (say, tens of thousand years) average deformation rate, but earthquake preparation process may be associated with the 'fluctuation' of such deformation rate at a shorter time scale, say, several decades. The second is that the deformation rate given by geodetic measurement has been accumulated only since the recent decade. Moreover, GPS measures only the horizontal deformation (on the surface). What is the present decades-scale deformation rate in deep, therefore, is still a question worthy to be explored using as much data as possible. In this work, we try to use microseismic data to investigate the present deep deformation rate of the Longmenshan fault zone and compare it with its neighboring Xianshuihe, Anninghe, and Zemuhe fault.

2. Data and Method Used for the Analysis

The study region of this work includes the Xianshuihe, Anninghe, Zemuhe, and Longmenshan fault zone, as shown in Fig. 1. In the figure, these fault zones are represented by polygons with the same area. Data used are from the Monthly Earthquake Catalogues provided by China Earthquake Networks Center (CENC). The catalogues span from 1970/01/01 to 2008/01/01, with a significant improvement of detection capability or catalogue completeness since 1977. The monthly catalogues are compiled based on the local seismological reports of

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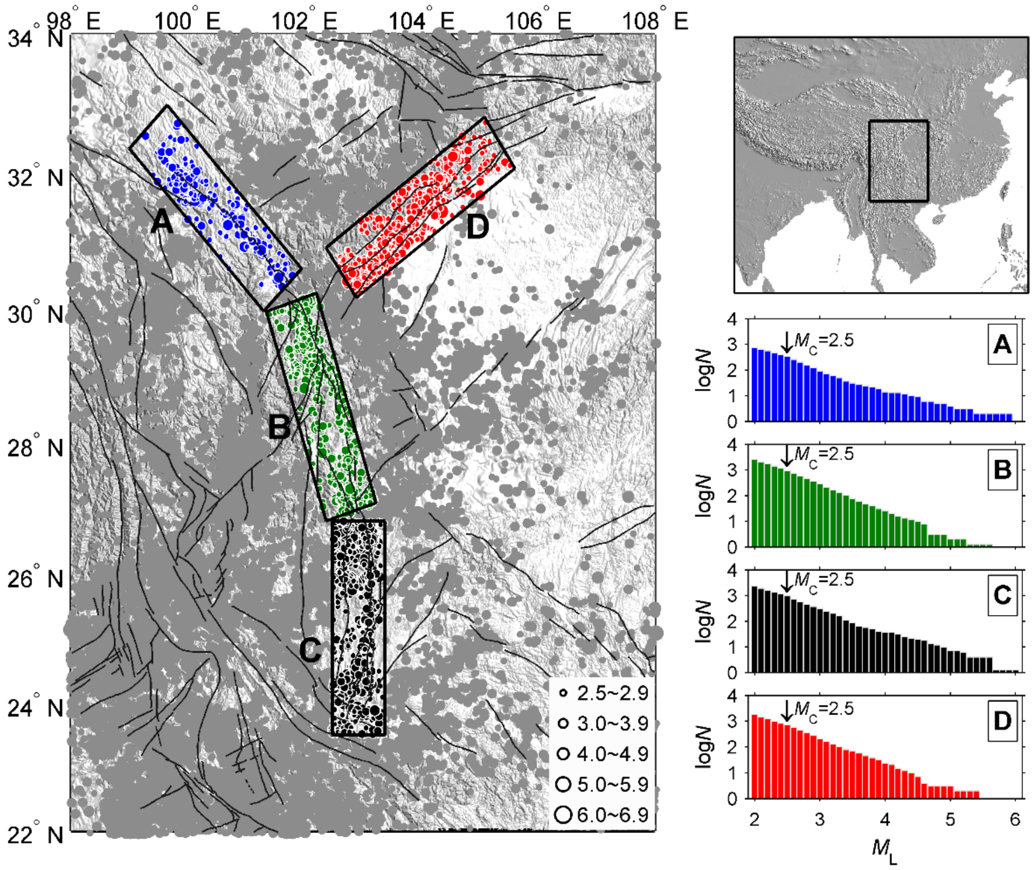

Fig. 1. Earthquakes with $M_L \geq 2.5$ in the Longmenshan, Xianshuihe, Anninghe, and Zemuhe fault zone and their vicinities for the period from 1977/01/01 to 2008/01/01, with active faults by dark gray lines. The region under study is displayed in the indexing figure to the upper right. In the figure, polygon A is the Xianshuihe fault zone, polygon B the Anninghe fault zone, polygon C the Zemuhe fault zone, and polygon D the Longmenshan fault zone. Gray and colored dots show the locations of events outside and inside the polygons, respectively. For comparison, the areas of the polygons are taken as the same. Frequency-magnitude distribution in these different fault zones during this period of time is displayed to the bottom right of the figure as an indication of the completeness of earthquake catalogues. Cutoff magnitude is marked in the figure as $M_C = 2.5$. In all the figures Chinese M_L is used as the unified magnitude.

provincial seismic networks, with magnitude unified as Chinese M_L. Cumulative-number analysis and frequency-magnitude analysis show that the completeness of these catalogues is M_L 2.5 after 1977, being consistent with the result of Yi *et al.* (2004, 2005, 2006) and Su *et al.* (2003). Lack of sufficient focal mechanism data prevents from using the standard Kostrov (1974) method to map the deformation rate, as what has been conducted for a much larger spatial scale by Qin *et al.* (2002). However, relative consistence of focal mechanisms in each polygon (see, e.g., http://www.globalcmt.org/CMTsearch.html; Xu, 2001; Zhao *et al.*, 2008) indicates that using microseismic data without considering the focal mechanism can still provide useful results about the deformation rate. In this study, as a straightforward and simplified approach, we compare the deformation rate of the Longmenshan fault zone with that of the neighboring Xianshuihe, Anninghe, and Zemuhe fault zone, to avoid the bias caused by the cutoff of the microseismic events under the completeness cutoff magnitude. Using the spirit of Kostrov method, we purposely take the polygons which represent the four fault zones to have the same area—In the map projection, we implement this equal-area property simply by shifting/rotating the polygon for the Longmenshan fault zone to the place of other three fault zones. Area selection is to some extent arbitrary, and the guiding rule for the selection of the width (vertical to the along-strike direction) of the polygon is that the 'whole' seismic event cluster of the Longmenshan fault zone be included, without the inclusion of that of the nearby Minjiang fault and Huya fault. As a result, the whole aftershock zone of the Wenchuan earthquake is included in this area. In this view, when we say Longmenshan fault zone here, we are mentioning the central- and north-part of this fault zone which accommodated the May 12, 2008 earthquake. We also varied this width and got similar results for these changes—the increase and decrease of a quarter of the area.

To evaluate the deformation rate for each fault zone under study, Benioff strain (Benioff, 1951; Utsu, 1961; Sykes, 1966), a somehow ambiguous but practically useful physical quantity, is calculated through the magnitude of earthquakes. Different authors gave various versions of such a conversion (for example, Robinson, 2000; Vere-Jones *et al.*, 2001). Here we take the conversion formulae of Kanamori (1977) and Robinson (2000), by firstly obtaining seismic moment from magnitude, secondly obtaining earthquake energy from the conversion of seismic moment to energy, and finally obtaining Benioff strain from the energy. Our focus is the comparison between the Longmenshan fault

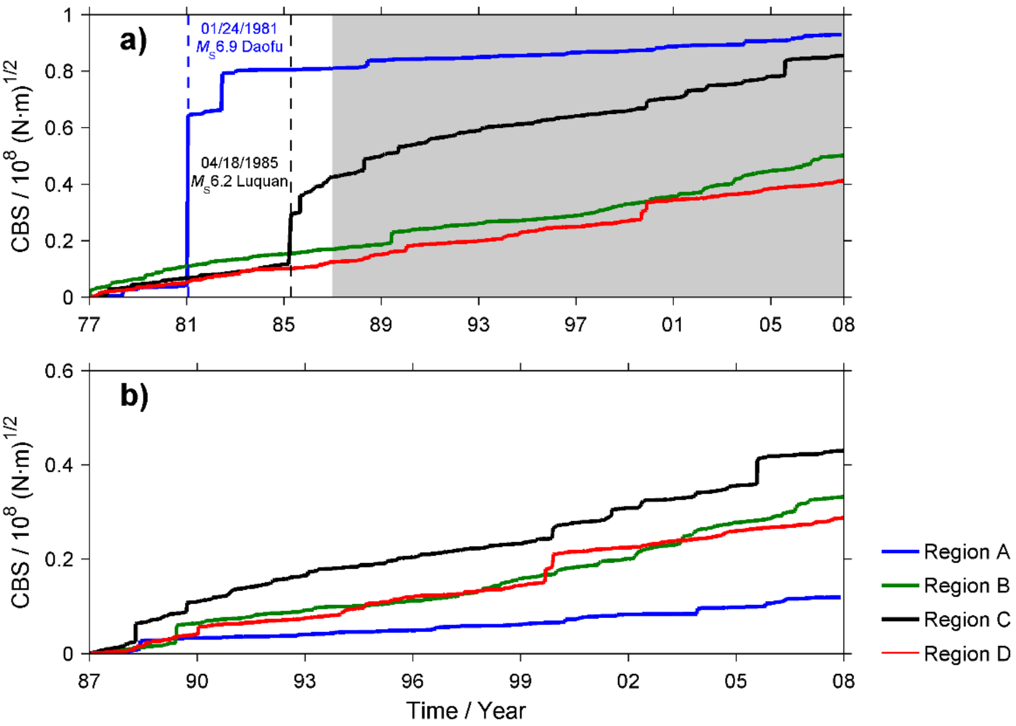

Fig. 2. (a) Cumulative Benioff strain (CBS) using earthquakes with $M_L \geq 2.5$ from 1977/01/01 to 2008/01/01 along the Longmenshan fault zone (Polygon D), together with those along the nearby Xianshuihe (A), Anninghe (B), and Zemuhe (C) fault zone for comparison. Blue and gray vertical dashed lines correspond to the 1981/01/24 Daofu M_S 6.9 earthquake and the 1985/04/18 Luquan M_S 6.2 earthquake, respectively. Shadow region shows the time window from 1987/01/01 to 2008/01/01. (b) Cumulative Benioff strain for the period from 1987/01/01 to 2008/01/01.

zone and its neighboring fault zones, therefore unit of the Benioff strain plays a minor role in the discussion. Because the same conversion parameters are taken for all these fault zones, the conversion from magnitude to Benioff strain does not affect the result of comparison even if the conversion formulae are problematic and the magnitude has uncertainties. In the study region, all the earthquakes are shallow ones. Considering the uncertainties of depth determination in the monthly catalogues, depth is not considered in the calculation of cumulative Benioff strain.

3. Benioff Strain of Longmenshan and Its Neighboring Active Fault Zones

Figure 2(a) is the cumulative Benioff strain curve for the period from 1977/01/01 to 2008/01/01 for region A, B, C, and D, respectively, representing the Xianshuihe, Anninghe, Zemuhe, and Longmenshan fault zone, respectively, with different colors to represent different groups of earthquakes, being consistent with Fig. 1. In the curves of the Benioff strain, there are two strong earthquakes shown, namely the January 24, 1981, Daofu M_S 6.9 earthquake in the Xianshuihe fault zone and the April 18, 1985, Luquan M_S 6.2 earthquake in the Zemuhe fault zone. These two strong earthquakes caused rapid increases of the cumulative Benioff strain curve. Removing the effect of these two earthquakes and focusing on the changing rate or deformation rate, as shown by Fig. 2(b) which zooms in the recent two decades, it can be seen that for the period from 1987/01/01 to 2008/01/01, deformation rate of region A, B, C, and D, as shown by their cumulative Benioff strain curve, are basically comparable. The Longmenshan fault zone has an even higher deformation rate than the Xianshuihe fault zone.

The difference between GPS estimate and seismic estimate of deformation rate may be worthy of discussion. For the strike-slip-dominated Xianshuihe-Xiaojiang fault, deformation rate estimated by seismic data (Ding, 1991), 9 mm/yr, is shown to be consistent with the deformation rate by GPS data, about 9 mm/yr (Wang *et al.*, 2003) or (9.8±2.2) mm/yr (Li *et al.*, 2003). However, for the high-dip-angle-thrust-dominated Longmenshan fault zone, apparently GPS measurement underestimates the deformation rate. As a matter of fact, having a close look at the result of Shen *et al.* (2003) and Jiang *et al.* (2003), it can be seen that although the shear strain rate of the Longmenshan fault zone is significantly smaller than that of the Xianshuihe, Anninghe, and Zemuhe fault zone, the principal strain rates of them are basically comparable. In the result of Qin *et al.* (2002), the high-scalar-strain-rate region associated with the Longmenshan fault zone is also remarkable. On the other hand, the difference between the geologically estimated deformation rates and the seismically estimated deformation rates may be due to the difference of time scales. Probably the short-time-scale variation may indicate some precursory process related to the preparation of the earthquake. But based on the present data we have to be careful not to go too far away in interpreting the results.

4. Conclusions and Discussion

For a long time, the Longmenshan fault zone has been considered as a 'quiet' one as indicated by its low deformation rate observed by geological studies and GPS observations. Questioning whether this conclusion holds for the real situation at depth because geological estimation deals with a very long time scale average, and GPS measurement deals with the horizontal deformation (measured at the surface of the Earth) only within the recent decade, we tried to take the approach similar to Kostrov method to investigate the deep deformation using data of microseismicity since the recent three decades. We used local earthquake catalogues to calculate the cumulative Benioff strain along the Longmenshan fault zone and considered the nearby Xianshuihe, Anninghe, and Zemuhe fault zone for comparison. The method is simple, but what is observed is interesting to some extent, that at the two decade time scale, different from geological process (ten thousand years) and GPS-observed deformation (less than one decade), considering both horizontal and vertical deformation, and comparing with its neighboring active fault systems, the Longmenshan fault zone seems not as 'quiet' as traditionally assessed. If the result is correct, then deformation rates based on background seismicity can be used as a complement to both GPS and geological results in the estimation of seismic hazard. Question proposed by this study is that, given the short span of observations of the very large events, it may not be possible to say if a much longer history over many earthquake cycles would indicate that the Wenchuan quake is truly more rare than similar events on other nearby faults marked as more active.

Comparison of seismic and geodetic data in the estimation of deformation rate has been conducted for other regions or other spatio-temporal scales (e.g., Ward, 1998a, b; Qin *et al.*, 2002; Leonard *et al.*, 2008) since recently. In such a comparison, it has to be cautioned that the assessment may be tricky when dealing with different time scales (Bennett, 2007). Distribution of earthquakes also affects the estimation of the moment release (Frohlich, 2007). For the Xianshuihe and Zemuhe fault zone under this study, whether the occurrence of the strong earthquakes in 1981 and 1985, respectively, depressed the microseismicity along these two faults is another question in need of further investigation. Also note that Longmenshan fault is a mega-thrust, and the other three comparing faults are strike-slip dominated. Therefore, how to interpret the result obtained needs more sophisticated considerations in both seismology and geodynamics.

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