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Preparatory mechanism of *M*s8.0 Wenchuan earthquake evidenced by crust-deformation data

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Abstract: Some crustal-deformation data related to the *M*s8.0 Wenchuan in 2008, was described and a model that is capable of explaining the observed deformation features is presented. The data include: pre-earthquake uplift in an area south of the epicenter obtained by repeated-leveling measurements; pre-earthquake horizontal deformation by GPS observation during two periods in Sichuan-Yunnan area; vertical deformation along a short cross-fault leveling line in the epicenter area; and co-seismic near-field vertical and horizontal crustal-movement data by GPS. The model is basically "elastic-rebound", but involves a zone between two local faults that was squeezed out at the time of earthquake.
Key words: Wenchuan *M*s8.0 earthquake; earthquake generation mechanism; deformation; leveling; GPS

1 Introduction

The *M*s8.0 earthquake that occurred in Wenchuan, on May 12, 2008 caused disastrous loss of life and property. This is the first thrust earthquake of magnitude 8.0 recorded in Chinese mainland since various crustal-deformation monitoring networks were set up there. We carried out a comprehensive study of these data, in hope to better understand the preparatory mechanism of this great thrust earthquake and its possible significance in earthquake prediction.

2 Pre-earthquake uplift shown by mobile leveling measurements

Figure 1 shows vertical deformation in an area south of the epicenter, based on a set of data from first-grade repeated leveling measurements with random error less than 0.5 mm per kilometer. This area has a mountainous complicated environment. Thus measurements for different sections cannot be repeated during some consistent time intervals. The repeat interval varied from 21 to 32 years with an average of 27 for the main circle. As a result, a velocity adjustment method was used, which resulted in an estimated standard error in vertical velocity of 0.04 mm/km/a . The reference point used is the cardinal bench mark in Yibin, Sichuan province[1,2].

The study area is located in the North-South seismic belt, which is a transitional zone between a relatively uplifted region in the west and a relatively stable region in the east. Because of the large crustal deformation here, it is difficult to find a stable bench mark as reference . So we could only analyze the main features of the relative changes. As shown in figure 1, there was a gradual increase in uplift from south to north. Even the reference point at Yibin was rising about 2 mm per year relatively to Pingdi in the south of this area. The rise around Litang and Qianning amounted to more than 7 mm/a, or a total of almost 200 mm during the average interval of 27 years. Further north is the epicenter, where no leveling data is available, but the trend should

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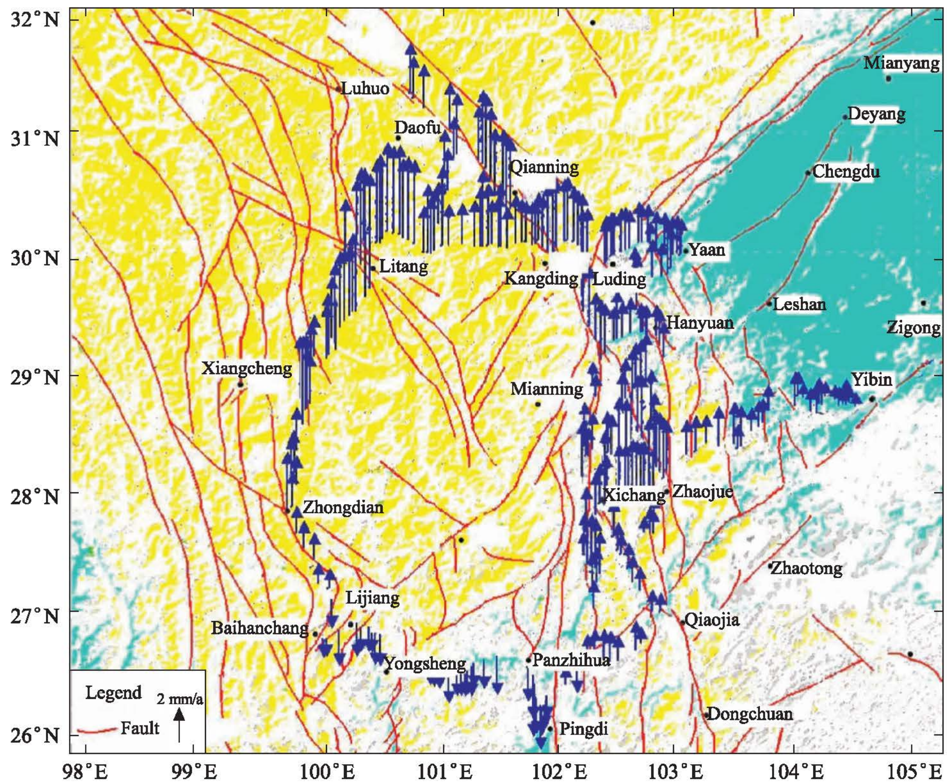

Figure 1 Vertical velocity of bench marks in Yunnan-Sichuan area

have continued. Thus may be assumed that, before the earthquake, the crust was deformed elastically and that the uplift reached 200 mm or more at the epicenter.

3 Pre-earthquake horizontal crust deformation

Based on the No-Net-Rotation principle[3], we processed the GPS data in 1999, 2001 and 2004 from a mobile regional network[4] in Yunnan-Sichuan region, and obtained horizontal-movement vectors during the two periods in this area (Fig. 2). The result shows that during these periods the western part was moving eastward rapidly while the eastern part remained nearly stationary, which is in accordance with other results[5,6]. This implies that Wenchuan area was under a strong west-east compression. We had noticed this feature in 2004 and suspected that a thrust earthquake would occur in Longmenshan fault zone, but did not give a definite conclusion[7]. The reason why we had misjudged the seismic situation was the long-term stability of this area (the stable Chengdu basin in the east, and the maximum historical earthquake recorded along Longmenshan fault had a magnitude of only about 6)[8-10] and a lack of experience about intra-plate strong thrust earthquakes. From figure 2 we can see now that, under the push of India plate, the NE movement of Qinghai-Tibet plateau diverged here toward N-NW and SE-S, respectively. This feature was due to the hindrance of Longmenshan fault zone, which was locked under a strong compression. To correspond with the uplift shown in figure 1, the uplift of ground surface, as a free boundary, in Wenchuan area should presumably have been larger.

4 Deformation shown by cross-fault measurements

Several short-baseline leveling sites were set up across Longmenshan faults, where we did some preliminary study more than 20 years ago[11]. No remarkable abnormal deformation appeared before the quake at most of these sites. This was understandable because the Longmenshan area rose up broadly under a long-term compression and, most of faults were locked and perpendicular to the stress direction, thus, the deformation could not be detected by the short-baseline leveling measurements. However, an anomalous change was recorded before the earthquake across Wenmao fault at the Gengda site (Fig. 3). After analyzing the data,

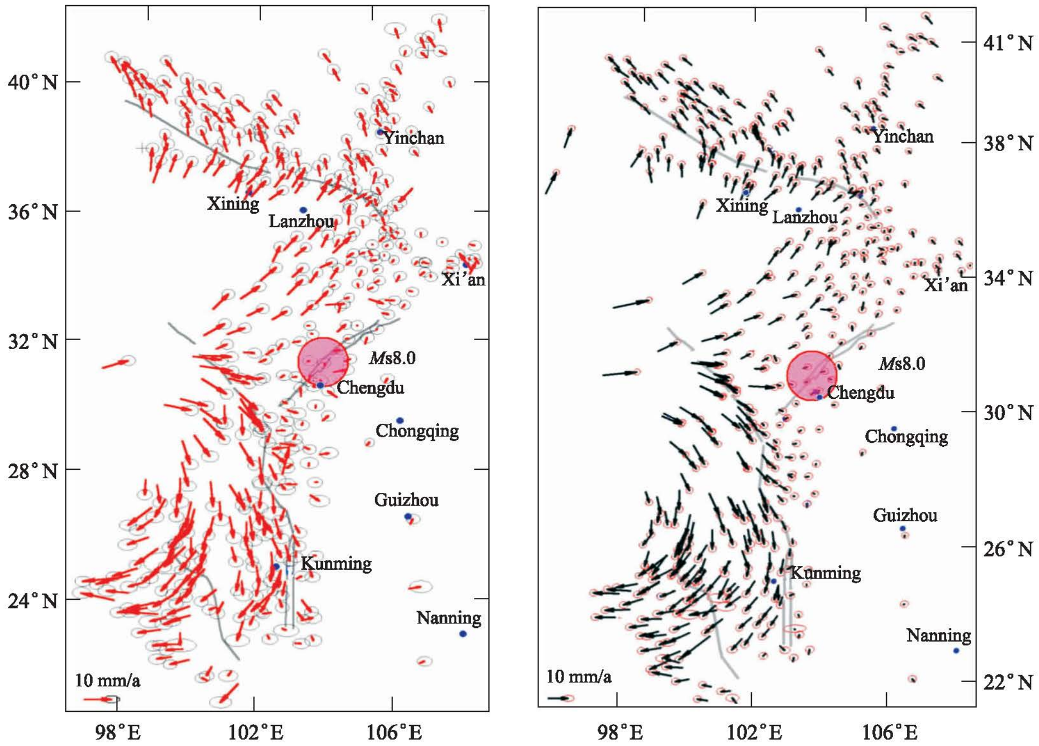

Figure 2 Horizontal deformation vectors from mobile GPS net in Yunnan-Sichuan area

we[11] pointed out that, although suspicious disturbing sources might have existed, there had been examples in which big-scaled deformation appeared and were accompanied by disturbances before great earthquakes[12,13]; it was thus difficult to prove quantitatively that such anomaly was induced only by disturbance. Thus it was permissible to conjecture that the anomalous change at Gengda was possibly induced by certain pre-earthquake fault-creep activity. A concern here is that the change shown in figure 3 implies that the Wenmao fault acted like a normal fault, whereas during the earthquake it showed thrust movement. If the recorded change was a precursor of the quake, how do we give an explanation for this apparent contradiction? This is one of the questions we attempt to consider later in this paper.

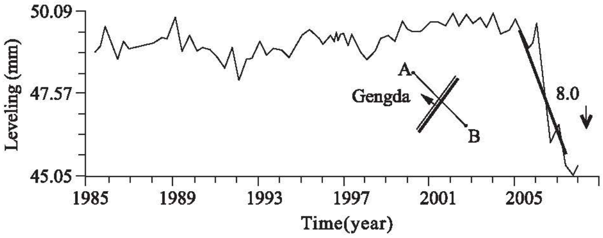

Figure 3 B-A leveling observation curve at Genda station

5 Near-field co-seismic deformation

After the earthquake, China Earthquake Administration (CEA), Bureau of Surveying and Mapping (BSM) of China and several other organizations promptly made some intensified re-measurements with different methods in order to know the size and distribution of co-seismic deformation. The results were announced in early September 2008, in a joint meeting of BSM and CEA[14]. Figures 4 and 5 show, respectively, the co-seismic horizontal and vertical vectors from GPS observation. From figure 4 we may see a much larger westward movement of the eastern foot-wall side than the eastward movement of the western hanging-wall side, in contrast to the long-term background crust movement in Chinese mainland, which shows a prominent northeastward movement of Tibet-Qinghai Plateau. From figure 5 we see a large subsidence of as much as 700 mm resulted from the thrust movement that should have caused uplift instead[14]. What is the mechanism responsible for these seemingly contradictory observations?

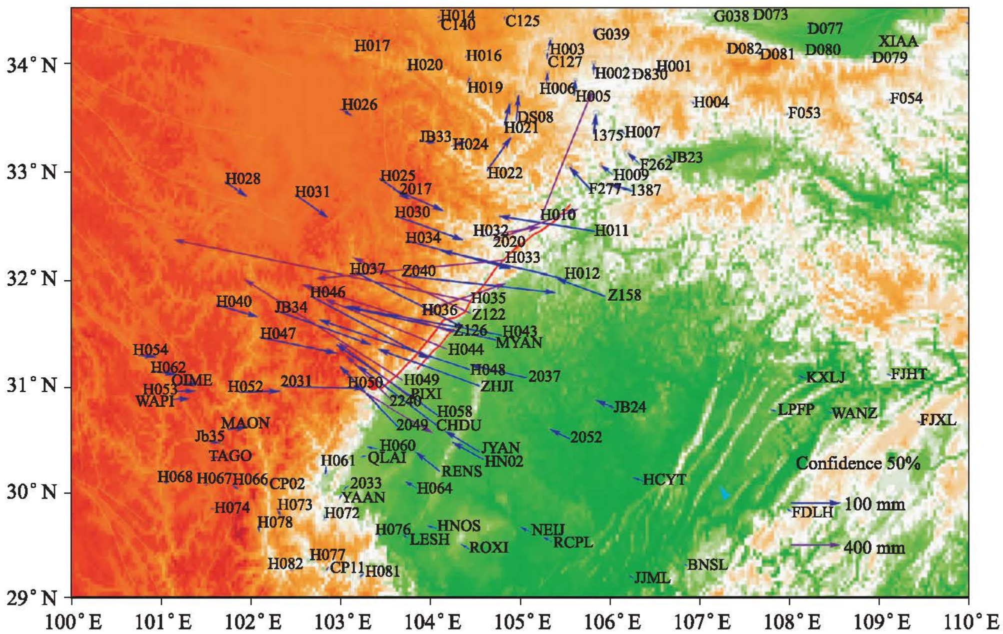

Figure 4 Co-seismic horizontal vectors of GPS

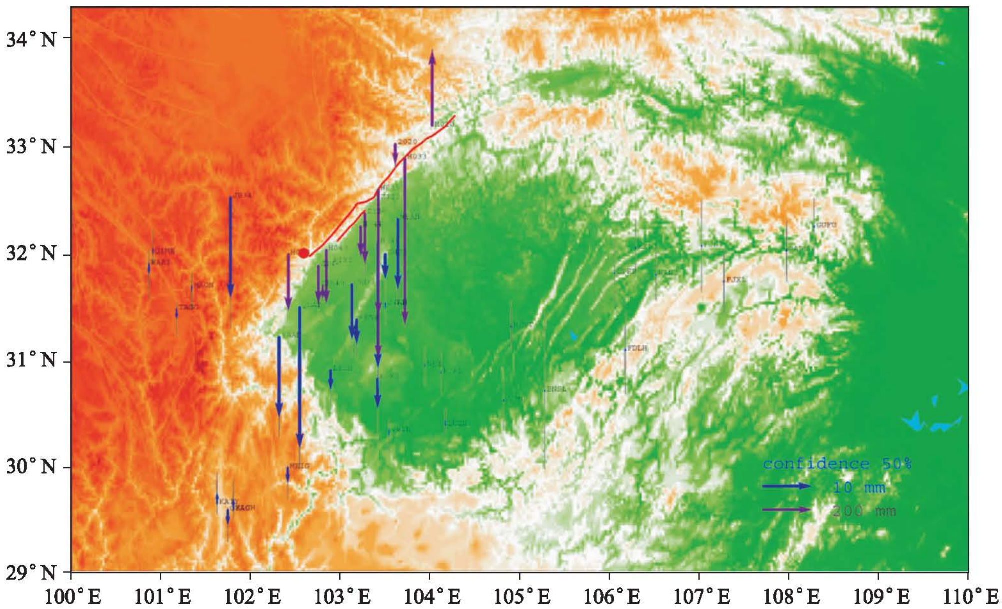

Figure 5 Co-seismic vertical vectors of GPS

6 A comprehensive explanation of the earthquake-preparation process and the observed crust deformations

There have been many studies on earthquake-generation mechanism, and the result accepted by most people is the elastic-rebound theory[15,16]. In the case of the Wenchuan thrust earthquake, the process involved an uplift caused mainly by a long-term horizontal compression and a sudden rupture in a direction nearly perpendicular to the compression. To give a reasonable and comprehensive explanation for the previously described crust deformations, we propose here a "Press-Up and Thrust-Down" model for this earthquake, and possibly other intra-plate thrust earthquakes (Fig. 6). Figure 6(a) is a sketch of "Press-Up" of the ground around three locked faults under long-term horizontal compression, until sufficient elastic energy was accumulated to cause some thrust-type ruptures. The "Press-Up" concept is supported by the results shown in figure 1 and figure 2.

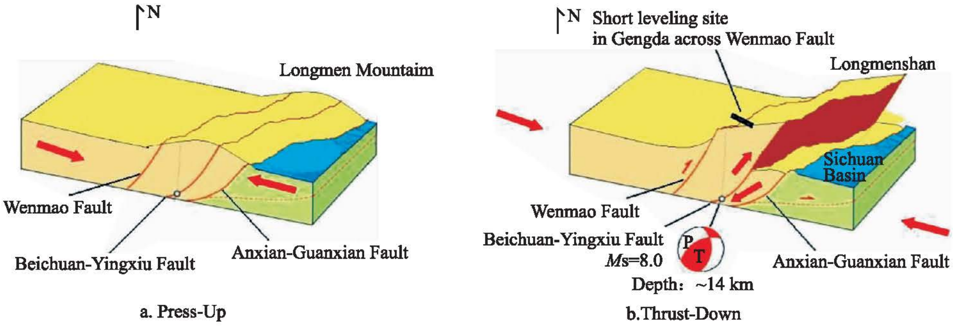

Figure 6 Press-up and Thrust-Down model for Wenchuan earthquake generation and occurrence

Figure 6(b) is a sketch of the co-seismic elastic rebound "Thrust-Down" movement at the Beichuan-Yingxiu fault; it converted horizontal compression to vertical shear strain and thrust movement parallel to the shearing direction. Before the earthquake, as the vertical shear strain was accumulating, thus some kind of fault-creep activity might have tended to occur. However, we do not have an direct evidence for this along Beichuan-Yingxiu fault because of lack of monitoring. However, this possible activity may explain the pre-earthquake normal-fault movement observed at the short-leveling site at Gengda across the Wenmao fault (Fig. 3). Some scholars attributed the observation at Gengda to certain house-building activity near the site[17], and we would disagree. First, in a large-scaled deformation process, there is usually a critical stage immediately before a major rupture, during which according to nonlinear theory the system is very sensitive to even very weak outside disturbance[12,13]. In other words, such rupture might occur sooner or later after a slight disturbance. Secondly, there is no sufficient reason or reliable evidence to show that ordinary house-building activity within tens of meters could have influenced in such remarkable way a bench mark that had been stable for decades. Although based on figure 3 alone it is very difficult to reach the right conclusion before the quake, afterward it is not difficult to conclude that the slight disturbance by the house-building activity might have served only as a possible trigger for the observed slip event at the critical stage. Thirdly, the reason that the normal-fault kind of leveling change was regarded by many as being induced by house building was that it was different from the expected thrust movement like the earthquake. However, according to "Thrust-Down" model presented herein, there is a local squeezed-up zone between Beichuan-Yingxiu fault and Wenmao fault (Fig. 6(b)), so that the large pre-earthquake movement of 4.26 mm could be a result of the squeeze-caused pre-slip. Otherwise, the normal faulting activity should have weakened, disappeared or become thrust in type. Yet in fact, the normal slip increased even to 243.1 mm[17]. This observation further shows the existence of a local squeeze-out zone caused by the particular condition in geological structure and stress environment, which required a model more complicated than purely "elastic rebound".

Sichuan basin belongs to the relative old foot-wall side, and it has always been pulled up passively by the hanging-wall side of the locked fault during the long-term compression. When the up-pulling force exceeded the critical force to cause the rupture of Longmenshan faults, the Wenchuan earthquake occurred, and the up-pulling force disappeared suddenly, resulting in a strong downward rebound for the foot-wall side in the Sichuan basin. Thus the pre-earthquake uplift decreased or disappeared and co-seismic subsidence occurred in the epicenter area near the faults, except some local uplift due to the thrust faulting movement. This subsidence was larger on the foot-wall side, because of the down-thrust action. Thus the co-seismic crust deformation shown in figure 4 and figure 5 may be reasonably explained .

7 Discussion

The "elastic rebound" model was proposed on the basis of crustal-deformation observation a long time ago, and is accepted widely [15,16]. The *M*s 8.0 Wenchuan earthquake is a very rare large thrust-type event that occurred in an inland area for which a relatively large set of crustal-deformation data were recorded. The results indicated that the earthquake ' s generation was basically in accordance with the " elastic rebound" model. But because of some special structural and stress conditions, the zone between Wenmao and Beichuan-Yingxiu faults was squeezed out near the epicenter. With the help of the crustal-deformation data recorded before and after the earthquake, we have proposed the "Press-Up and Thrust-Down" model, which may better explain the various complicated phenomena of crustal deformation recorded before and after the quake; it may help us to better recognize the complexity and variety of the development process of earthquakes, provide some new understanding for the crustal-deformation mechanism, and illustrate the existence of diversity among different earthquake occurrences.

Not-being aware of the coming of the great Wenchuan earthquake was a big blow to many of us who hoped to recognize certain regularity in earthquake preparation and occurrence. Many scholars had the opinion that there was no premonitory information recorded at all. This study shows , that this is not true. Our problem was that due to the lack of similar experience we did not recognize beforehand the complexity of a great inland thrust earthquake, nor did we know what kind of pre-monitory signals to expect. This is a critical deficiency of the our current earthquake-prediction efforts, which are based mainly on experiences. The occurrence of Wenchuan earthquake brought not only regrettable disasters and shocks, but also data and opportunity for study. We should cherish and make full use of these precious data and this rare opportunity.

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