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Anomalous crustal movements before great Wenchuan earthquake observed by GPS

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Abstract: Studies of GPS data carried out before and after the great Wenchuan earthquake of *M*s8.0 on May 12, 2008 show that anomalous crustal movements occurred before the earthquake. Data from 4 pre-earthquake observation sessions at a dense network of stations show that there were prominent broad-ranged long- and mid-term anomalies in horizontal displacements and strain and in vertical displacements. Data from the fewer-numbered reference stations of continuous GPS observations since 1999 in West and South China showed short-term preseismic anomalies in horizontal displacements. The detection of co-seismic horizontal displacements at these stations supports the existence of the pre-earthquake anomalies. Results of single-epoch solutions of data from continuous-observation stations near the epicenter also show large imminent anomalies in vertical displacements. Although the Wenchuan earthquake was not predicted, these results give a strong indication that GPS should be the main observation technique for long-term, mid-term, short-term and imminent earthquake predictions.

Key words: Wenchuan earthquake; earthquake prediction; GPS; crustal movement, horizontal displacement; vertical displacement

1 Introduction

CMONOC (Crustal Movement Observation Network of China) is one of the major scientific engineering projects for the 9th Five-Year Plan in China, in which GPS is the main observation technique and the earthquake prediction the main goal. The current China Mainland Tectonic Environment Monitoring Network (CMTEMN) is the second phase of CMONOC. It includes 25 reference stations of continuous GPS observations that began in March 1999, 1000 regional stations that were observed for 5 sessions in 1999, 2001, 2004, 2007 and 2009 at intervals of 2 - 3 years, and 56 basic stations that have been resurveyed annually.

The *M*s8.0 Wenchuan earthquake (31.0° N, 103.4° E) occurred on May 12, 2008 right in the North-South seismic belt where many regional GPS stations had been established (Fig. 1). This provided a most favorable condition for observing the crustal movements before and after such a great event since the beginning of GPS observation in the world. Whether precursory crustal movements were detected by this GPS network before this event is of vital importance for testing not only the applicability of GPS in earthquake prediction but also the possibility of earthquake prediction in general. Based on our long-time experience in GPS data processing and analysis for earthquake prediction, we not only identified some pre-earthquake anomalies in the continuous GPS data recorded at the reference stations[1], but also by using the results of the 2007 GPS observation that was obtained 10 days after the Wenchuan earthquake and the results of the previous observation obtained some convincing preseismic a-

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nomalies in horizontal crustal deformation within 3 days[2,3]. In the first half of 2009, we further explored imminent pre-earthquake anomalies by using single-epoch solutions from continuous GPS observations at a sampling rate of 30 s at GPS stations near the epicenter, and obtained some interesting results[4]. At the end of 2010, we obtained significant vertical crustal movements before the event by reanalyzing the vertical displacements in the regional network.

In this paper, we describe the method used and the results obtained in our analysis of GPS data to study the premonitory crustal movements for the Wenchuan earthquake.

2 Data processing and analysis

At the CMONOC Data Center, all GPS data have been processed with GAMIT/GLOBK software to get solutions in the global reference frame. The data processing in this paper mainly refers to data processing and analysis we performed, in addition to the solutions of the Data Center, for the purpose of earthquake prediction and related studies. We have also used the BERNESE software to process the original GPS data to get single-epoch solutions, which were used for further data analysis.

The analysis of precision and reliability of the results of GPS data processing is prerequisite for further data processing and analysis. Analysis of the results of a large amount of data processing at the Center shows that the precision has reached international level, and the results are reliable. For example, for weekly solutions at the reference stations, the RMS in the horizontal components is about 1 – 2 mm, and that in the vertical components is about 3 mm. The precision of data-processing results for the regional stations is basically the same[3,5].

In order to analyze precursory crustal deformation, appropriate methods must be used to get information of the crustal movements or deformations, including the selection of reference frames for displacements, calculation of displacements and strain components, analysis of time series, spatial distribution of deformation, statistical analysis and deformation models. In order to give an objective analysis of the anomalies, the data-processing methods used must reflect the observed results factually, by avoiding or minimizing the loss of fidelity.

In order to give a reasonable explanation for the regional relative crustal movements, regional reference frames (or standards) are used in Europe and North America. For example, SNARF (Stable North America Reference Frame) has been used in North America for the study of the displacement fields[6]. Displacement solutions in the regional reference frames can be obtained from the solutions in the global reference frames through similarity transformations. In order to maintain the stability of the reference frame, i. e., the coordinate system, in both global and regional reference frames, the selected core stations (or reference-frame stations) must have good long-term linear velocities, particularly in the horizontal components. While the differences in velocity between different global core stations could be large, the velocity differences between regional core stations are relatively small on account of their lower linear velocities; this helps to keep the regional reference frame more stable. Some core stations, especially global core stations, that cannot keep good linear velocities as time passes will be deleted. Thus the number of core stations selected in the global reference frame of a certain period is gradually decreasing, and this increases the errors or uncertainties for solutions in the global reference frame. On the other hand, the core stations in the regional reference frame can remain unchanged or little changed. The displacement solutions in the regional reference frame can eliminate some common mode errors in the global reference frame, and this is equivalent to certain kind of filtering. In addition, the noise level in the displacement solutions of the regional reference frame is relatively low[7]. In GPS data processing, particularly for regional networks, several global reference frames have been used for different periods; they include IGS97, IGS00, IGb00 and IGS05. However, the change of the global reference frames does not influence the results of displacements in the regional reference frames.

Since horizontal and vertical displacements follow different patterns, it is more appropriate to use different regional reference frames for each[1,5]. The core stations in the regional reference frames used in this paper were selected from GPS stations in the stable eastern part of Chinese mainland[1,3,8].

Horizontal and vertical displacements are usually obtained from GPS observations at first, from them other deformation components can then be calculated; they include various components of baseline and strain, some of which are independent of the reference frames. In this study, we have analyzed mainly displacements and strains in a regional reference frame and on an ellipsoidal reference surface[9]. One of the features of horizontal displacements is that they clearly show interactions between different stations, as well as crustal interactions between different blocks or regions; for example, they show clearly Indian plate's northward pushing of the Chinese Mainland.

By using Delaunay Triangulation, consecutive but non-overlapping triangles can be formed from GPS stations. The displacements in each triangle are used to calculate various strain components to be the representives at the center of the triangle, including 2 principal strains, azimuth of the maximum strain, the 1st and 2nd shear strains, the surface expansion and the spin. In strain calculations, some unreliable results caused by configuration differences of the triangles must be deleted[3]. The reason why triangles are adopted for strain calculations is to avoid fitting errors caused by exceeding 3 stations; large fitting errors would indicate that the calculated strains are not representative of the area covered by the GPS stations. As shown in rock-fracture experiments, shear strains are most relevant to earthquake occurrence.

Besides time series of deformation, some spatial distributions are also fundamental for the studies; they include horizontal displacement vectors, vertical displacements, discrete or contour maps of various deformation component, strain tensors and fitting surfaces. By using the trend-surface analysis of the GMT software developed by Paul Wessel of the University of Hawaii and Walter Smith of the National Oceanic and Atmospheric Administration, we may obtain colored maps of various spatial patterns of deformation components. These maps can properly show the deformation trend reflected in the discrete points, and reveal regions of outstanding deformation at a glance. This method is basically similar to the method of contour mapping, but the results are shown more intuitively. Thus trend-surface mapping is one of the main methods used in this paper. However, results of trend-surface mappings outside Chinese Mainland are not considered in this paper.

Because the mechanisms or models of crustal deformations are not sufficiently understood, statistical data analysis is often used commonly as a method to identify earthquake precursors. Statistic analysis also shows that for certain periods and in certain area, some deformation components, particularly strain components, are uneven and random. They are caused not only by observational errors but also by complicated deformation mechanism.

3 Long- and mid-term pre-earthquake crustal-deformation anomalies detected by regional network

3.1 Horizontal crustal movement

Figure 1 shows the horizontal displacements detected by the regional network in Chinese Mainland from 1999 to 2004; more than 150 selected core stations were used in the displacement solution, all of them located in eastern China. The most striking feature of the displacements before the Wenchuan earthquake is that the earthquake occurred in the North-South earthquake belt where the easterly movements diverges, that is, the part north of the epicenter moved in the NEE direction while the part south of the epicenter moved in the SEE direction, with smaller displacements near the epicenter. The horizontal displacements recorded at regional and reference stations in 2007 before the Wenchuan earthquake show that the main tectonic driving force of the earthquake was the northward push of the Indian plate, and secondarily by the push of plates on the east and south sides[1,3].

Figure 2 shows maps of accumulated 1st shear strain at discrete points (at the centers of the triangles in strain calculation) in Chinese Mainland; these maps show the anomalies and their development during four successive periods from 1999 to 2007. In order to show the anomalous changes before the earthquake clearly, the accumulated co-seismic and post seismic strain of absolute values larger than 1.0×10^{-6} that were associated with the Kunlun Mountain earthquake of $Ms8.1$ on November 14, 2001 are deleted in the figure. The area framed by the red rectangle in each figure shows approximately the extent of anomalies[3]. The map on the top right shows the anomalous strain values at discrete points for the period of 1999 to 2004, whereas the map at the bottom right shows the corresponding trend-surface mapping. The anomalous area is obviously more striking in the trend-surface map.

The distribution of accumulated 1st shear strain shows

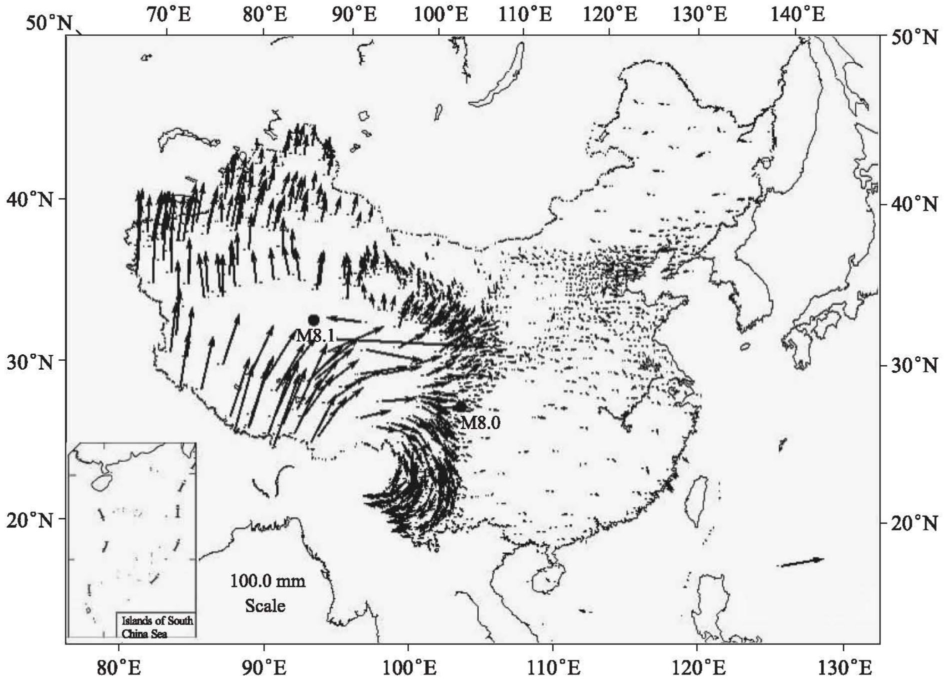

Figure 1 Horizontal displacements in Chinese Mainland from 1999 to 2004. The black dots indicate epicenters of the Kunlun Mountain and Wenchuan earthquakes; the large displacements (arrows) are co-seismic and post-seismic displacements associated with the $Ms8.1$ Kunlun Mountain earthquake in 2001

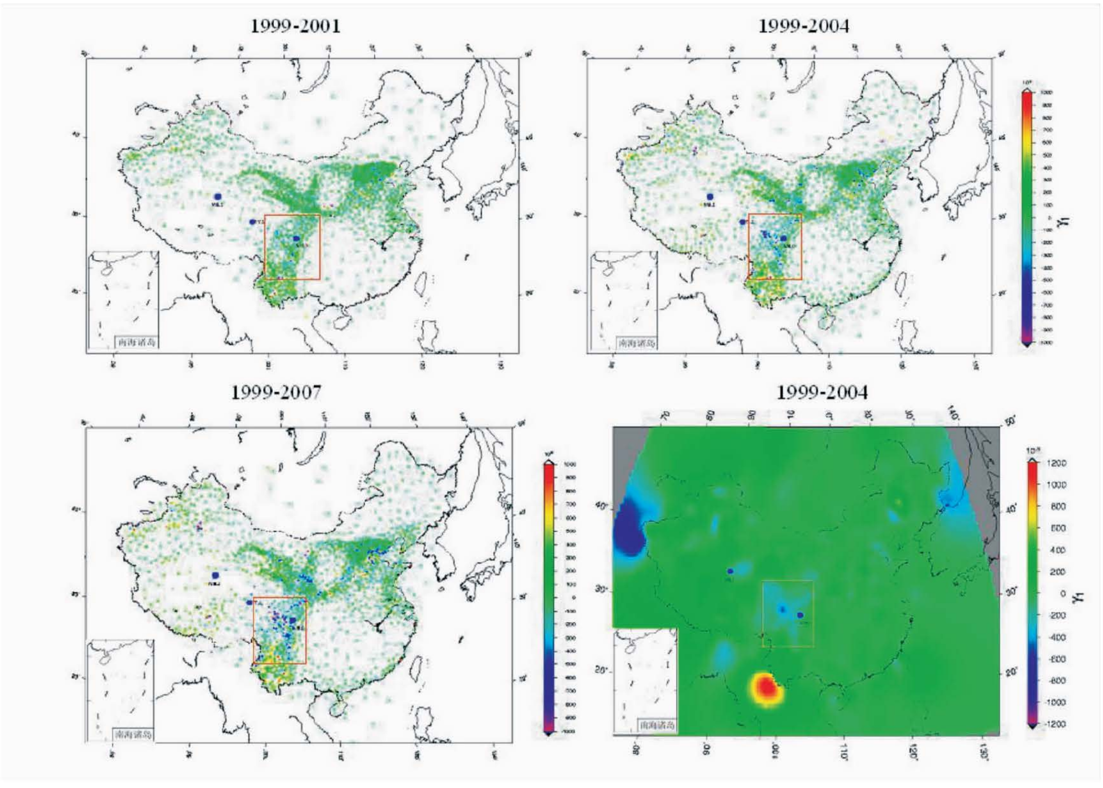

Figure 2 Accumulated 1st shear strain before the Wenchuan earthquake in Chinese Mainland. The red rectangle indicates the approximate area within which anomalies were observed in the GPS data from 1999 to 2007

that except the area in and around the epicenter of the Kunlun Mountain earthquake, the most obvious accumulation during 1999 to 2007 occurred in an area west of the Wenchuan earthquake; it involved more than 300 triangles formed by more than 300 GPS stations in an area extending for 1100 km in the NS direction and 960 km in the EW direction. The anomaly began to emerge in 2004 and then increased in extent and amplitude to a maximum of -9.0×10^{-7}, which is more prominent than that obtained from trend-surface mapping. The Wenchuan earthquake occurred at the northeastern edge of a small area of relatively large accumulated compression within this anomalous area. The reliability of the observation of horizontal strain anomalies around the Wenchuan earthquake is further supported by the later-mentioned analysis of interference in vertical displacements recorded at the regional stations.

Statistically, the areal dilatation and the 1st and 2nd shear strains usually show normal distributions, whereas the earthquake magnitudes and accumulated maximum shear strains show Poison distributions within a certain region and period. But deviation from these distributions may occur before large earthquakes[3]. Such a deviation was also observed in the statistics of the strain accumulations in the above-mentioned anomalous area, mostly bounded by 98° and 105°E in longitude and 28° and 36°N in latitude (involving more than 200 triangles within the rectangle in Fig. 2). Figure 3 shows statistical distributions of the accumulated maximum shear strain in 4 different regions for 4 different periods. Each diagram shows the ratio of the number of triangles having a certain maximum shear strain to the total number of triangles in a region for a period the strain in units of 1.0×10^{-7}. It may be seen in figure 3 that the strain distribution in the Wenchuan region during 1999 to 2007 deviates significantly from the Poison distribution, in contrast to the ratios in the whole network, in East China and in the Yunnan region. In the bottom-right diagram of figure 3, the ratios for 3 intervals in the green rectangle are almost the same and are larger than in other intervals, which is an indication of significant strain accumulations before the earthquake. Although the pre-earthquake strain accumulations were random and uneven in space, their trend became increasingly clear when approaching the earthquake occurrence.

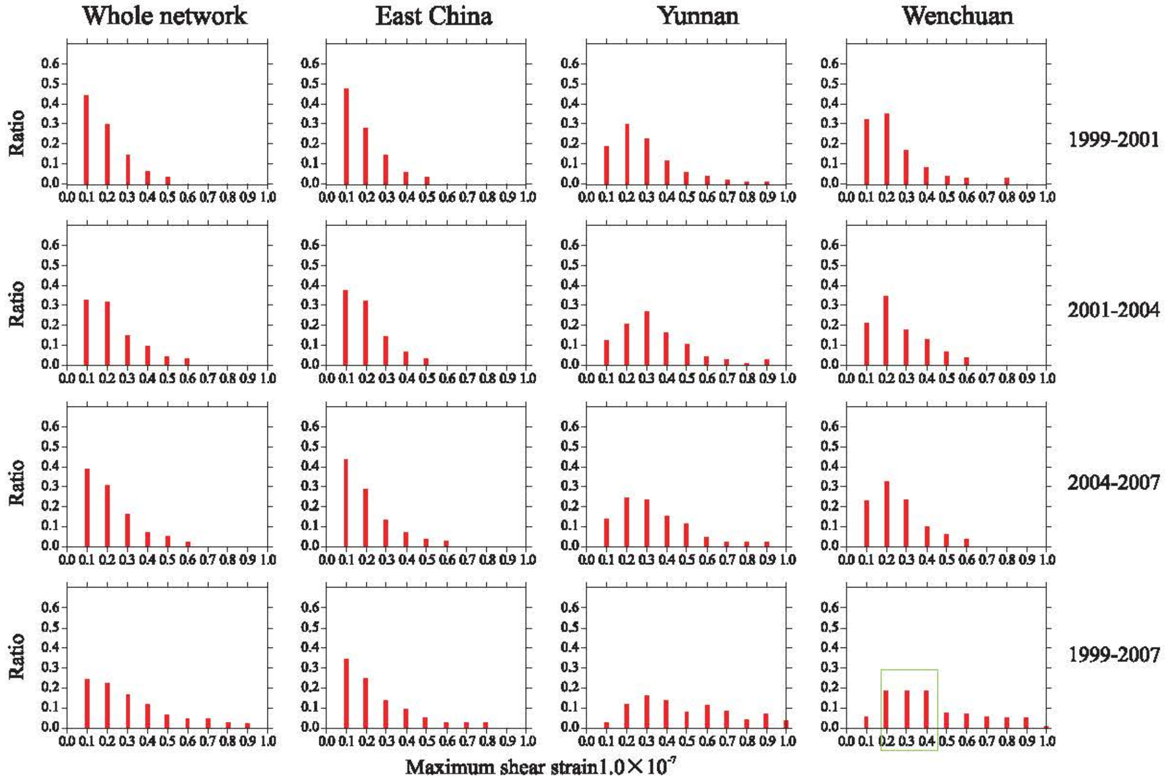

Figure 3　Comparison of statistic distributions of accumulated maximum shear strains in different regions and for different periods. The ordinate indicates the ratio of the number of triangles in each strain interval to the total number of triangles in a region and for a period; the abscissa shows the maximum accumulated shear strain

3.2 Vertical crustal movement

Whether vertical displacements observed by GPS can be used in the study of earthquake precursors is also an interesting problem. Compared with leveling measurements, GPS has some special advantages: Observation can be made frequently, even in real time; high precision; and no distance-related error accumulation. In the regional network, there has been 5 sessions of GPS observations during a relatively long period, providing much data favorable for the study of the general trend in vertical displacements[10]. Because of the large number of regional stations, 23 stations in the eastern region were selected as the core stations for vertical displacement solutions. The velocities at these stations were in the range of –0.5 mm/a to 0.5 mm/a; the maximum changes at these stations from 1999 to 2009 are required to be less than 15 mm, which is obviously quite strict.

In the analysis of vertical tectonic movements, care must be taken to avoid certain environmental interferences, such as groundwater pumping and mining, which can result in gradual subsidence of the stations or benchmarks in a certain area. The effect of such subsidence on horizontal displacements at different stations is complicated. For example, in the area of subsidence caused by groundwater pumping in North China, no gradual horizontal displacement or strain accumulations similar to those before the Wenchuan earthquake appeared (Fig. 2). This kind of subsidence is certainly detrimental to detecting pre-earthquake trend of horizontal strain accumulations. In the regional network, except H008, H032, H033, H035, H044, H045 and H049 in the Wenchuan earthquake region and H161 in Yunnan, all stations with subsidence of more than –100 mm during 1999 – 2009 are located in North China. This is because of large amounts of groundwater pumping that occurred there; the largest subsidence amounted to 1261 mm by 2009. The 8 stations in the Wenchuan earthquake region recorded large amount of subsidence not before the earthquake, but afterward, mainly by co-seismic displacements. The change at H161 in Yunnan was not large but similar to that at the subsiding stations in North China. Fortunately there is only one such station in Yunnan and it does not affect the results of our trend-surface mapping.

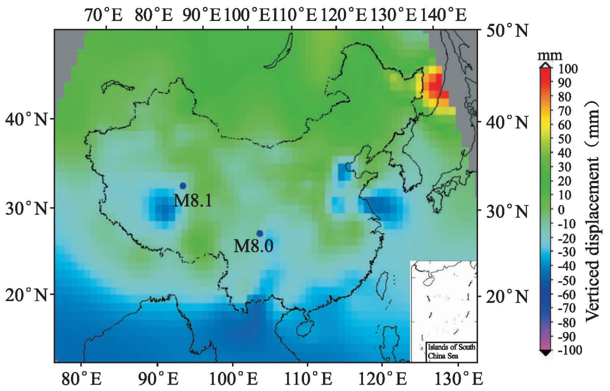

Figure 4 Vertical displacements in Chinese Mainland from 1999 to 2007.

In order to eliminate or minimize the influence of such large vertical displacements on the analysis of smaller vertical displacements, only vertical displacements in the range of –100 mm to +100 mm were used in the trend-surface mappings. Among the 3 eliminated stations with uplift of more than 100 mm in 2009 is H010, which recorded co-seismic uplift in the northern part of the earthquake region. The numbers of stations eliminated from the results of data processing in 2001, 2004 and 2007 are 6, 23 and 43, respectively; they all showed subsidence of more than –100 mm and were outside the earthquake region; 53 stations of such large subsidence were eliminated from the result of 2009, including the above-mentioned 8 stations in the earthquake region. Figure 4 shows the result of trend-surface mapping of the vertical displacements in Chinese Mainland from 1999 to 2007.

Figure 4 reveals 3 areas of prominent subsidence in Chinese Mainland. Despite the above-mentioned restriction in data selection, the subsidence in North China started to appear in 2001. Since 2007, there has been significant subsidence in the area southwest of the Kunlun Mountain earthquake that occurred in 2001, this subsidence was recorded only at a few stations due to low station density in this area (Fig. 1). The station density is high in the subsidence areas southeast and southwest of the Wenchuan earthquake, especially along the South-North earthquake zone (Fig. 1). No interference was identified except at some individual stations, such as H161 in Yunnan.

The subsidence near the Wenchuan earthquake was significantly different from that of the other 2 subsidence areas, particularly in areal extent and shape. The change was significant not only during a period that spanned the earthquake occurrence, but also prior to the earthquake. Some GPS stations that subsided before the earthquake turned to uplift after the event. The subsidence in the large area southeast of the earthquake started in 2004, with amplitude of about −40 mm at several stations. The appearance of this subsidence area coincided in time, but not in space, with the the appearance of the area of anomalous strain accumulation (Fig. 2). In 2007, the amplitude of subsidence decreased, and the northern part of the subsidence area along the North-South seismic belt became narrower while the southwestern part expanded. The continuous-observation stations PIXI, JYAN and NEIJ that recorded anomalously large subsidence within an hour before the earthquake are also located right in this subsidence area[4].

Stations with co-seismic subsidence exceeding −100 mm are clustered in the area north to the main shock. The subsidence reached −721.6 mm at station H033 189 km north of the epicenter, and −178.6 mm at station H050 only 24.5 km from the epicenter. The area with smaller subsidence extended northeastward along the aftershock zone. The only station with uplift of more than 100 mm is located north of the epicenter.

Before the earthquake the vertical displacements in the area north of the epicenter were not significant, suggesting that the northern segment of the Longmenshan fault was locked in vertical motion before the earthquake. After the earthquake, the aftershock activity in this part was higher than in the southern part, and with larger magnitudes; it extended farther in the northeastern direction. This is characteristic of rupture extension of a locked segment.

It should be emphasized that the selections of core stations only affects the overall upward or downward movement of the region, not the relative movements within the region. In other words, the selection of core stations doesn't influence the result of the above-mentioned analysis.

4 Short-term horizontal-displacement anomalies detected at reference stations

There were only 25 reference stations that had relatively long sets of data, which could be used for weekly solutions of high precision in time series analysis. Although most of the stations were far away from the epicenter, anomalous horizontal displacements were identifiable at reference stations in West China in January or February, 2008. These anomalies were characterized by block motions in a wide area; almost all the N components sped up simultaneously before January 2008; after which there were turnarounds, some occurring simultaneously. In addition, unusual westward movement appeared at GUAN in Guangzhou and QION in Qiongzhong in southern China, and anomalous changes also appeared at stations of KMIN in Kunming and XIAG in Xiaguan[1]. During the anomalous period the displacements were small, the maximum being about 20 mm in NS component and only 5 mm in EW component without obvious regularity. The stations showing typical anomalous changes were DLHA in Delingha, DXIN in Dingxin, XNIN in Xining and XIAA in Xi'an (Tab. 1 and Fig. 5). The anomalous changes at these 4 stations are characterized by synchronous changes of the same pattern in N component: rapid northward movements at first and then at the beginning of 2008 the movements slowed down or even turned southward. Although XIAA is not a core station for horizontal movement, it is located within the area covered by core stations; thus the regional reference frame obtained from similarity transformation for this station is quite reliable. The duration of the anomalies is estimated to be about 9 months, from August 2007 to early May 2008.

No significant anomalies were identified at reference stations in North China, including LUZH, which was relatively near the Wenchuan earthquake. There are also stations of continuous GPS observations near the earthquake, such as PIXI mentioned below, but the results of processing of their weekly or daily (except on the day when the earthquake occurred) data from early 2008 to the earthquake occurrence don't show any significant anomalies.

Large co-seismic displacements have been observed generally at GPS stations in the epicenter areas of many large earthquakes; significant co-seismic horizontal displacements have also been observed at GPS stations far away from the epicenters. Co-seismic displacements, which occur clearly, suddenly, and synchronously with the corresponding earthquakes, are considered the most convincing crustal movements. In the present study, the process of the pre-seismic and co-seismic horizontal displacements detected at reference stations far away from the Wenchuan earthquake suggests that these displacements are elastic rebound in nature[1], and substantiates the existence of the pre-seismic anomalous horizontal displacements. After the earthquake, on the basis that the co-seismic horizontal displacements were in opposite sense to the pre-seismic displacements, it was concluded that the earthquake had released energy in a large area, and all the anomalies were related with the event. As a result, worries about earthquake risks in other regions were ruled out.

Table 1 Epicentral distances of several reference stations (unit: km)

LUZH	305	YANC	838
XIAA	631	DLHA	898
XNIN	639	DXIN	1143

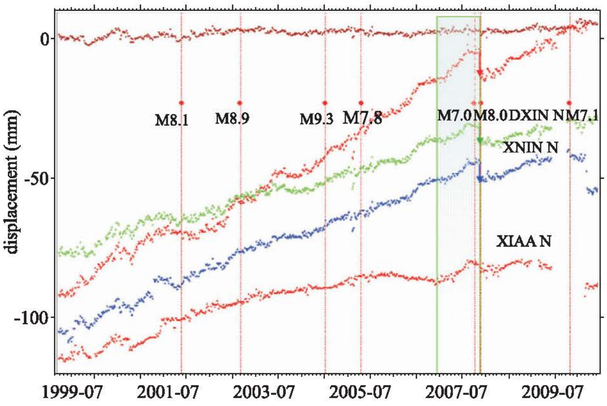

Figure 5 Displacement time series for N component at DLHA, DXIN, XNIN and XIAA from March, 1999 to early December, 2010. The shaded area indicates the duration of significant anomalies before the Wenchuan earthquake; arrows indicate co-seismic displacements. YANC is one of the reference and core stations.

In order to test whether the observed co-seismic horizontal displacements are reliable, not false rotational displacements resulted from observation errors at the core stations, we compared the results of 2 different similarity transformations: (1) The core stations had both horizontal displacements and rotations; (2) they had only horizontal displacements. The results shows that most of the time before the earthquake, the displacement trends in both cases are the same, that no obvious rotations were caused by observation errors, and that the pre-seismic anomalies are real. Shortly before the earthquake a minute rotation could be seen. The co-seismic rotation was significant though small, the largest rotational displacement at stations in West China was less than 20 mm. At reference stations in West and South China, the pre-earthquake displacements were in opposite sense to the co-seismic displacements. In plate tectonics, plate rotation is a major way of plate motion, which is expressable with Euler rotational vectors. It is difficult to deny rotation being a possible way of co-seismic displacement. Since the Wenchuan earthquake there has not been any horizontal displacement similar to these co-seismic horizontal displacements recorded at so many stations at the same time (Fig. 5). This shows again that the co-seismic horizontal displacements were not caused by false rotation resulted from observation errors at the core stations used in similarity transformations.

No significant co-seismic or pre-seismic short-term anomalies in vertical displacements were detected at the reference stations. At some reference stations the annual variations disappeared or changed before the earthquake for some unknown reason.

In general, the development of the crustal movement before a large earthquake can be seen from the time series of the horizontal displacements at reference stations. The time when the displacements turn from speed-up to slow-down or change to opposite sense could be used to estimate the timing of the coming earthquake. The displacement process before and after the earthquake at some reference stations are quite similar to the deformation process before and after ruptures in rock mechanics experiments.

5 Imminent pre-earthquake crustal-movement anomalies detected at continuous-observation near epicenter stations

To search for imminent pre-earthquake anomalies, we used the BERNESE software in early 2009 to get the so-called single-epoch solutions from GPS observations at a sampling rate of 30 s. We used the reference station LUZH near the epicenter and 4 nearer continuous-observation stations PIXI, CHDU, JYAN and NEIJ in Sichuan to get single-epoch solutions from double differences, and by using the far away reference station YANC as the fixed station. The results show that the diurnal variation at LUZH became anomalous on May 9 and that the vertical displacements at PIXI, JYAN and NEIJ changed even more anomalously within an hour before the earthquake[4]. Figure 6 shows the time series of pre-earthquake N (North), E (East) and U (Up) displacement components from the single-epoch solutions at PIXI, only 36 km from the epicenter. The change in vertical displacement was more than 300 mm. By showing changes in all 3 components together in the figure is helpful to illustrate the reliability of the calculated vertical component. According to statistics, the precision is about 10 mm in the calculated horizontal components and about 30 mm in the vertical components.

It will take a long time before the method may possibly be used in earthquake prediction; a prerequisite is that GPS data can be acquired and processed in real time, which requires better data-processing software.

6 Discussion

A large amount of pre-earthquake crustal deformation data was obtained from GPS observations for the Wenchuan earthquake, the most outstanding being anomalies in the 1st shear strain accumulations appeared in the area of dense GPS stations around the epicenter. At the same time, significant subsidence occurred in another non-overlapping area. Short-term pre-earthquake horizontal displacement anomalies were detected at reference stations in a rather large area in West and South China. The reliably recorded co-seismic horizontal displacements at these stations showed themselves to be elastic rebound in nature, and provided convincing evidence for the existence of the pre-seismic anomalies. From the single-epoch solutions of continuous GPS observations at 3 stations near the epicenter we obtained some imminent large vertical-displacement anomalies. The pre-earthquake horizontal displacements at the regional and reference stations indicated that Chinese Mainland had been compressed by northward pushing of the Indian plate, and also by plates on the east and south sides at the same time. These anomalies were the manifestation of a long-term deformation development in the epicentral region under the driving force of the plate motions, which fostered a favorable condition for the earthquake occurrence. Before the earthquake, there was a period of intensification of crustal deformation in a rather large area with rapid accumulation of strain energy; imminently before the event there appeared a loss of stability at the epicenter, which led to the earthquake. Our results showed that the tectonic movements before the earthquake were mainly horizontal displacements, which clearly manifested the interactions between different plates, blocks or regions. In contrast, the vertical displacements might only be secondary effects of the horizontal movements. In addition, there were reportedly anomalies in TEC (Total Electron Content) calculated from data of continuous GPS observations in Sichuan[11]. All these anomalies were closely related with the Wenchuan earthquake in both time and space.

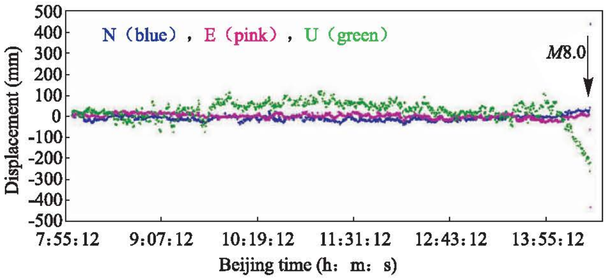

Figure 6 Time series of N, E, U displacement components from single-epoch solutions before the Wenchuan earthquake detected at the PIXI station of continuous GPS observations. The displacements during the last 2 epochs are co-seismic displacements

Compared to previous geodetic observations, the GPS crustal-deformation observations before the Wenchuan earthquake were unprecedentedly large in areal extent, long in duration, high in precision and high in temporal and spatial resolutions. The results should be reliable enough to withstand any further scrutiny. However, all such results are piecemeal and discontinuous in both time and space, reflecting only changes in different regions extents during different periods. Due to a lack of dense network of continuous-observation GPS stations of high sampling rate in Chinese Mainland, it has been impossible to get integrated pictures of crustal deformations with high temporal and spatial resolutions for a long time in a large area. Crustal deformations are the combined results of many factors, including stresses, strength of the medium and structures of the crust. It has been difficult or may be even impossible to get detailed information of these complicated factors that can be used to explain the observed results better.

The earth crust is where earthquakes occur; earthquakes and crustal movements are naturally and closely related; and GPS with the highest precision is currently the most favorable technique for monitoring crustal movements. Wenchuan earthquake's not being predicted was the result of many factors. However, the results of the present study show that GPS should be the main observation technique for long-, mid-, short-term, and imminent earthquake predictions. The main task in the promotion of earthquake prediction is to bring the GNSS (Global Navigation Satellite System), including Beidou from China, into full play. All the existing stations of continuous observations should be fully used, and new stations should be added. Break through in real-time data processing of GNSS observation is highly anticipated. In the meantime, because of limitations in observation, we must acknowledge that earthquake prediction is a most difficult scientific problem and that long-term research and development efforts are required.

Acknowledgments

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