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The *Ms*7.0 Lushan earthquake and the activity of the Longmenshan fault zone

Meng Xiangang and Liu Zhiguang

First Crust Monitoring and Application Center, China Earthquake Administration, Tianjin 300180, China

Abstract: The *Ms*7.0 Lushan earthquake is directly related to the activity of Longmenshan fault zone. In this article, deformation monitoring data in Longmenshan and its surrounding areas were analyzed and the result shows that the activity trend of Longmenshan fault zone depends on the relative motion between Bayan Har Block and Sichuan Basin, and the main power of the movement comes from the Tibetan Plateau and the upper Yangtze craton massif of push. In recent years, the Longmenshan and its surrounding areas is one of the main seismogenic area in mainland China. In this paper, combination with seismogenic area of geological structure and crustal deformation observation data analysis results, the relationship between the earthquake and Longmenshan fault zone activity was discussed, and the key monitoring areas in the next five years were proposed.

Key words: Lushan earthquake; Bayan Har Block; Longmengshan fault zone

1 Introduction

The *Ms*7.0 intense earthquake occurred in Lushan County, Sichuan Province, on April 20, 2013. This earthquake is the latest intense earthquake occurring in the southwest section of the Longmenshan fault zone after the *Ms*8.0 Wenchuan extra-intense earthquake in 2008. According to preliminary inversion results of the source rupture process issued by the Qinghai-Tibet Plateau Institute and the Institute of Geology and Geophysics of the Chinese Academy of Sciences as reported in relevant scientific research, this earthquake was caused by rupture of a thrust fault with a source depth of 10.2 km that was relatively concentrated in the fault plane. The main shock and aftershock were distributed along the Pengxian-Guanxian fault zone in the southwest section of the Longmenshan fault zone and were located in the Coulombic stress increase area of the Wenchuan earthquake occurring on May 12, 2008. The sources of both earthquakes have approximately the same nature and are dominated by thrust faulting, indicating that the Lushan earthquake is closely related to the Wenchuan earthquake[1]. In this paper, we analyze the deformation monitoring data of the Longmenshan fault zone and its surrounding areas, and we conclude that the activity trend of the Longmenshan fault zone depends on the relative movement between the Bayan Har Block and the Sichuan Basin and the movement energy comes from pushing by the Qinghai-Tibet Plateau and the upper Yangtze craton block. We analyze the observation data of geological structure and crustal deformation in the earthquake area to discuss the relationship between this earthquake and the activity of the Longmenshan fault zone, and we propose key monitoring areas in the next 5 years.

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Corresponding author: Meng Xiangang, E-mail: grapenun@163.com
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2 Relevant structure and earthquake

The Bayan Har Block is located on the northeast margin of the main region of the Qinghai-Tibet Plateau and is one of the areas with the most intense current earthquake activity in China. Its surrounding fault zones include the east Kunlun fault zone, the Mani-Yushu fault zone, the Xianshuihe fault zone, and the Longmenshan fault zone. Since the *M*s7.9 Mani earthquake occurring on November 8, 1997, a series of strong earthquakes have occurred in succession on the fault zones around the Bayan Har Block, including the *M*s8.1 earthquake occurring on the west of the mouth of the Kunlun mountains on November 14, 2001, the *M*s8.0 Wenchuan earthquake occurring on May 12, 2008, the *M*s7.1 Yushu earthquake occurring on April 14, 2010[2] and the *M*s7.0 Lushan earthquake occurring on April 20, 2013 (Fig. 1). The fewer earthquakes occurring in the Bayan Har Block show that this block has strong integrity, with fewer inside rupture activities. Further studies are needed to determine whether there is some trigger function responsible for these strong earthquakes successively occurring on the fault zones around the Bayan Har Block in such a short time period[3]. In this paper, we primarily study the relationship between this latest earthquake and the activity of the Longmenshan fault zone, and thus we study the activity of the earthquakes around the Bayan Har Block, to allow us to provide monitoring suggestions.

3 Activity of the Longmenshan fault zone

The Longmenshan fault zone is located in the junction belt between the northeast margin of the Qinghai-Tibet Plateau and the upper Yangtze craton block inside the Eurasian plate. It forms an obvious borderline between the Sichuan basin to the southeast and the mountainous area in the east of the Qinghai-Tibet Plateau to the northwest[4], and on its west is the Bayan Har Block. This fault zone is mainly composed of three trunk faults, i.e., a rear mountain fault, a main middle fault, and a front mountain fault, of the Longmenshan Mountain and a nappe structural zone in the transverse direction; it can be divided into three sections in the longitudinal direction: the Beichuan-Ningqiang and Mianxian section in the northeast, the Beichuan-Dujiangyan section in the middle, and the Dujiangyan-Luding and near-Kangding section, respectively[5]. After the Quaternary, the strong uplift of the Qinghai-Tibet Plateau and its generated lateral compression caused the Sichuan-Qinghai block in the northeast of the plateau to glide SEE. This gliding block not only led to compressional uplift of the Minshan Mountains along a SN strike on its east margin but also caused strong activity

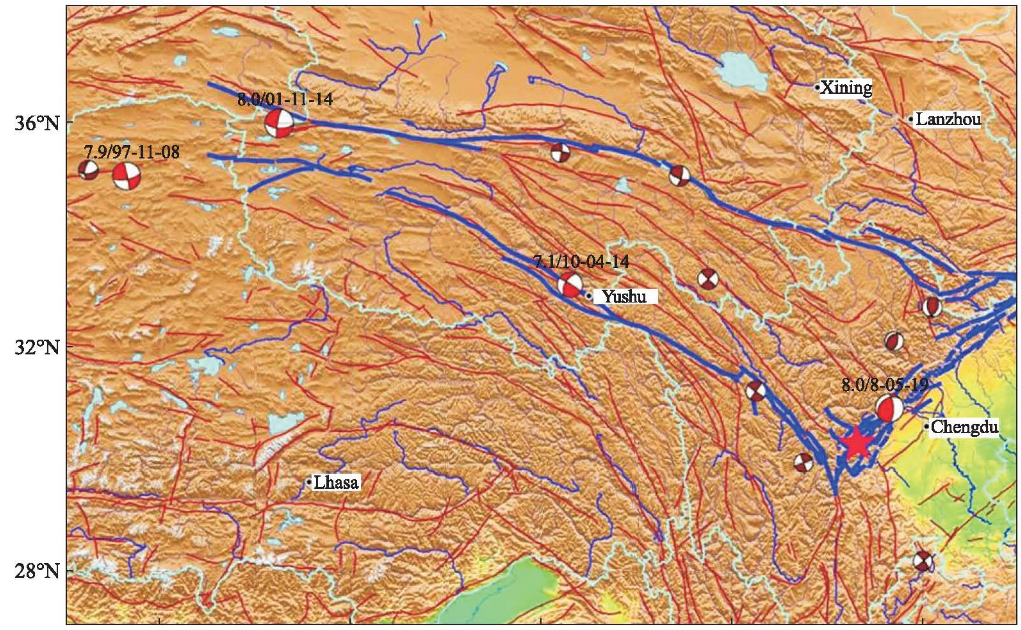

Figure 1 Earthquakes around the Bayan Har Block since 1997 (Blue lines are the active faults around the block, focal mechanisms are from Harvard CMT catalog)

of the middle and southwest sections of the Longmenshan fault zone owing to the limitation and blocking by the uplift of Minshan Mountain; they jointly constituted the active boundary on the east of the Sichuan-Qinghai Block, whereas the northeast section of the Longmenshan fault zone was discarded, and its activity weakened obviously and had tended to cease since the Late Pleistocene[6]. The *M*s8.0 Wenchuan earthquake and the *M*s7.0 Lushan earthquake occurred on the middle and south sections, respectively, of the Longmenshan fault zone[7]. In recent years, with the rapid development of geophysical prospecting technology, depth measurement accuracy with the earth has dramatically improved. Previous research results show that the mean upper crust thickness of this block is 18.80 km, the mean middle crust thickness is 10.50 km, the mean lower crust thickness is 15.3 km, and the mean crust thickness is 44.60 km[8].

Since the special project "China Comprehensive Geophysical Field Observation-the East Margin Region of the Qinghai-Tibet Plateau" was carried out, a great number of observation data have been acquired through precise level survey and regional Global Navigation Satellite System (GNSS) survey, and they have provided a solid scientific basis for obtaining the vertical deformation field image, the horizontal deformation field image, and the underground substance transport field image of this region. In this paper, we mainly analyze the variations and trends of the crustal deformation field in the Longmenshan fault zone and its surrounding areas by studying the deformation monitoring results.

3.1 Vertical deformation velocity field

In this research project, we conducted a precise level survey of more than 10000 km along the east and northeast margin regions of the Qinghai-Tibet Plateau, mainly covering the south and north earthquake zones, including the Longmenshan fault zone, the Xianshuihe fault zone, and the Zemuhe fault zone. According to the observation data, and using the previous results, the long-term vertical deformation velocity image of the Longmenshan fault zone and its surrounding areas were obtained (Fig. 2). The followings can be concluded: (1) The Sichuan Basin is in a descending trend as a whole, with a descending rate of 1 mm/a; whereas the east margin region of the Qinghai-Tibet Plateau exhibits an uplift trend, with an ascending rate of 4 mm/a. (2) The uplift rate of the Bayan Har Block is less than that of the Sichuan-Yunnan region on the east margin of the Qinghai-Tibet Plateau and is also less than that of the Haiyuan Block on the west margin of Ordos, the Lanzhou Block, the Xining Block, the Gonghe Block, and the Qaidam Block, and the uplift of the east and north margins of the Qinghai-Tibet Plateau is in wave form as a whole (with the uplift rate of the Bayan Har Block being less than that of the blocks on both its sides). (3) With the Longmenshan fault zone as a boundary, the upper wall ascends and the lower wall descends, which is consistent with the movement trend of the Qinghai-Tibet Plateau thrust by the Sichuan Basin; it is noteworthy that the earthquake-occurring background at the dogleg boundary is extremely similar to the warning-sign background of the Tangshan earthquake occurring in 1976; in other words, both of them are on the junction belt of the crust uplift and decline[9], with a difference that the vertical velocity field image of this region has lower resolution (data from two phases of 1970 and 2011) and the vertical deformation field image before the Tangshan earthquake has higher resolution (data from three phases of 1970, 1972 and 1975). In Haicheng earthquake prediction, the level data reflect the impending earthquake lockup very well. (4) It is not difficult to find that regional precise level survey data are very effective in obtaining the vertical deformation information of thrusting faults, which is reliable and can be directly viewed, so a regional precise level survey is an important monitoring method for vertical crust deformation monitoring. Therefore, the frequency for observing the Longmenshan fault zone needs to be increased; level observing sections for the Longmenshan fault zone can be set up, and real time (1 – 2 phases per year) tracing observation can be carried out with an observation period of 5 years.

3.2 Horizontal deformation velocity field

From the regional GNSS observation data of the projects "Continental Tectonic Environment Monitoring Network of China" and "Crustal Movement Observation Network of China", the horizontal deformation velocity image of

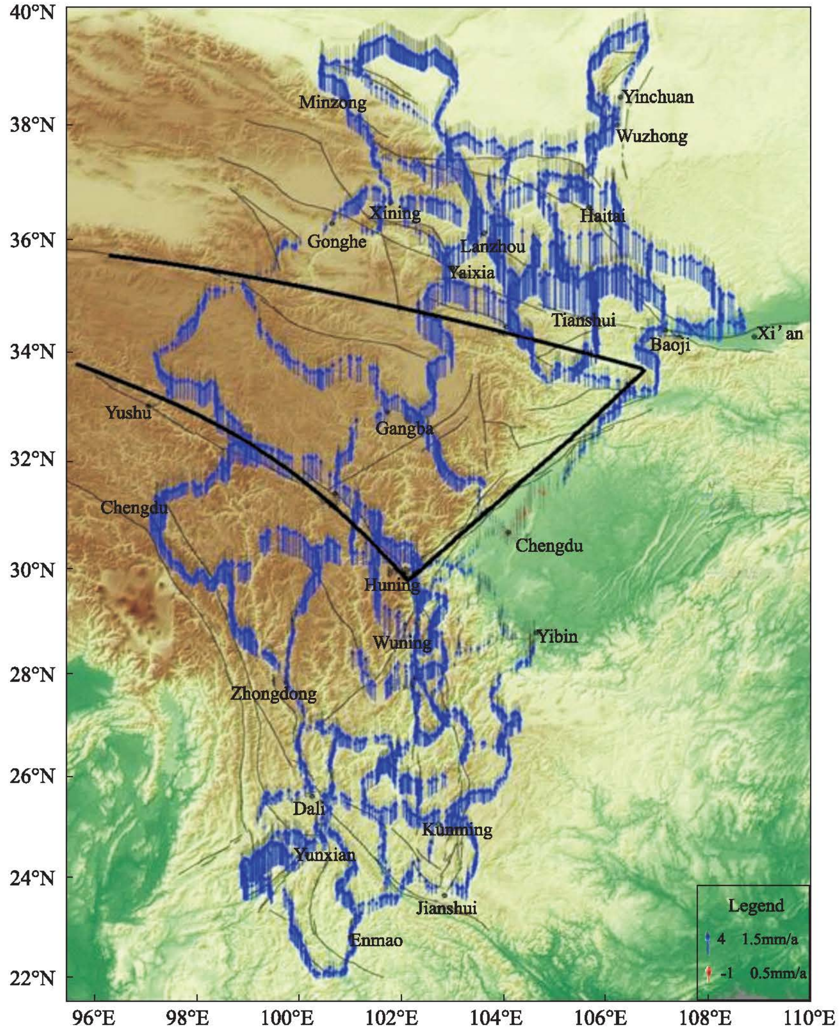

Figure 2 Recent vertical crustal deformation rates in Longmenshan and its surrounding areas from 1970 to 2011

the crust of the Longmenshan fault zone and its surrounding areas were obtained[10] (Fig. 3), and the movement trend and background of the crust are consistent with the conclusions from most current scientific researches[1-3]. Thus the following results can be inferred: (1) The east margin region of the Qinghai-Tibet Plateau is trending clockwise as a whole, and the horizontal deformation of the Bayan Har Block points to the Sichuan Basin in the northeast area and varies toward the northwest direction in the middle area, roughly exhibiting a radicalized shape. (2) The horizontal displacements on both sides of and near the Longmenshan fault zone are roughly identical, indicating that the surface of the thrusting fault zone has an unobvious horizontal displacement and may be in a lockup state. (3) The junction between the Longmenshan fault zone and the Xianshuihe and Anninghe fault zones has a relatively obvious slip trend. The rate of horizontal movement of the Bayan Har Block relative to the Qiangtang block is low so that the middle and east sections of the Xianshuihe fault zone are in a sinistral slip movement mode, and the north section of the Anninghe fault is also in a sinistral slip movement mode; the rate of horizontal movement of the Bayan Har Block relative to the Qaidam Block is high so that the east Kunlun fault zone is in a sinistral slip movement mode; the eastward displacement rate of the Bayan Har Block lies between the displacement rate of the Qiangtang Block and that of the Qaidam Block as a whole. (4) It is not difficult to see that the GNSS survey is important for monitoring slip-type movement of fault zones. Therefore, monitoring of the fault zones around the Bayan Har Block needs to be enhanced by adding observation points and distributing them in pairs as much as possible on both

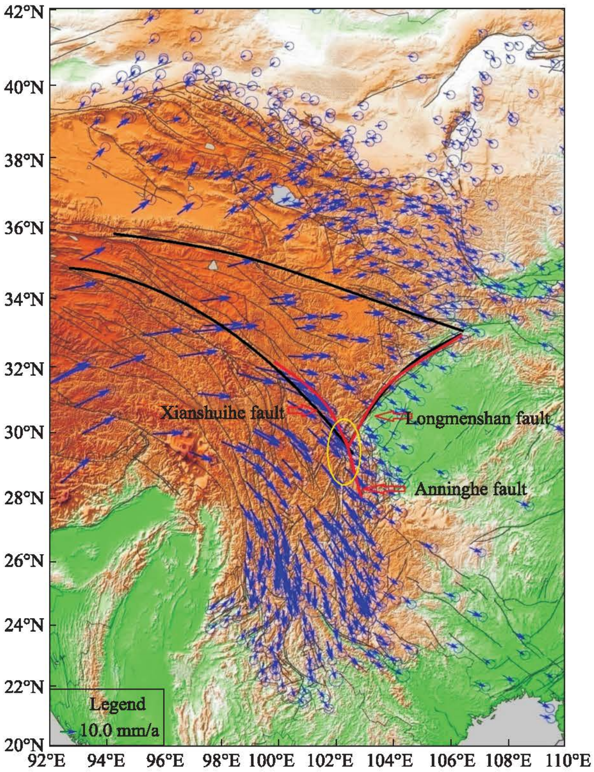

Figure 3 Crustal horizontal deformation rates in Longmen Mauntain and its surrounding areas from 1999 to 2012

sides of each fault zone with a monitoring emphasis on the middle and east sections of the Xianshuihe fault zone, the north section of the Anninghe fault, the middle and south sections of the Longmenshan fault, the middle and east sections of the east Kunlun fault zone, the east section of the Margaichace fault zone, and the west end area of the Bayan Har Block.

3.3 Brief summary

Synthesis of regional precise level and GNSS data analysis results of the east margin of the Qinghai-Tibet Plateau and the surrounding areas of the Longmenshan fault zone reveals the followings: (1) With the joint effect of the Bayan Har Block and the Sichuan Basin, the Longmenshan fault zone exhibits a thrusting movement trend, the mean vertical uplift rate and mean horizontal movement rate of its upper wall reach 4 mm/a and 10 mm/a, respectively, and the mean sinking rate and mean horizontal movement rate of its lower wall reach 1 mm/a and 5 mm/a, respectively. (2) The horizontal movement rate is basically identical near the Longmenshan fault zone, indicating that the area may have entered a lockup state. (3) The southwest section of the Longmenshan fault zone exhibits a composite movement of thrusting and slip, possibly due to the unloading effect of the NS slip of the Anninghe fault on the Longmenshan fault zone. (4) The vertical deformation velocity of the middle and east parts of the Bayan Har Block is less than those of the Qiangtang and Qaidam Blocks and the horizontal displacement rate lies between those of the Qiangtang and Qaidam Blocks, indicating that the Bayan Har Block still has a displacement in the EN direction as a whole, and the Xianshuihe and east Kunlun fault zones have evident slip trends.

4 Earthquake-inducing model

The *Ms*7.0 Lushan earthquake was induced under the joint effect of the surrounding blocks on the Longmenshan fault zone, so it is important to interpret the cause of this earthquake by establishing a model of various blocks inducing the earthquake according to the above discussion. To establish an earthquake-inducing model, we first make the following assumptions: (1) The structure of a single block in the Longmenshan fault zone is assumed to be a solid body of low compression and extreme breakability under overstress and has a given elastic modulus (weighted elastic modulus of rocks constituting the block) for which Coulomb's law is applicable[4, 11]. The influence of the gaps and voids in the single block on the integrity of the individual block is neglected, the single block is assumed to be cutting the rupture plane during cutting, and its compression rupture induced an earthquake. (2) The structure synthesized by multiple fault blocks of the Longmenshan fault zone is assumed to be fluid; when compressed by other blocks around it, it flows along the fault zone. In the stress concentration area, because of the blocking by large block structures around it, it exhibits a whole or partial rising movement in the vertical direction, and it flows toward weak stress areas in the horizontal direction. After the stress is released, the compressed block becomes denser and moves downward under the effect of its own weight, and upward, downward, left, or right relative movement is exhibited between the block and the adjacent compressed blocks or the block and the adjacent large fault zones under unloading, so as to induce aftershocks. (3) Regardless of whether the main shock or aftershocks are the result of fault rupture occurring in the rocks of the fault plane or block, creeping slip does not cause an earthquake here (Fig. 4)[12]. (4) Since earthquake epicenters are mostly in deeper parts underground, the confining pressure of the rocks at the rupture is very high; the larger the confining pressure, the less obvious the dimension effect of rock strength is; in other words, the confining pressure can reduce the degree of sensitivity of the dimension on the rock material strength. With the increase in dimension, the influence of the inhomogeneity of rock masses decreased gradually in the rock body, and the influence of structural planes such as joints, beddings, and faults increased gradually[13].

5 Coseismic deformation analysis

After the Lushan earthquake, we collected the 1-Hz observation before and after the earthquake from the "Continental Network" GNSS continuous station and the "Sichuan GPS Observation Network" continuous station near the source, and processed them using the precise single-epoch positioning software on the "Continental Network" data-processing platform, obtaining the near-field coseismic displacement field results[15] (Fig. 5). The observation data from the "Continental Network" GNSS continuous station were from days 102 – 113 of 2013, and those from the "Sichuan GPS Observation Network" continuous station were from days 108 – 111 of 2013, and the earthquake occurring time was 0:2:46 AM on day 110 of 2013, GPS time; the observation data from the above stations in the first hour of the very day of the earthquake are discarded. The following conclusions can be obtained from the figure:

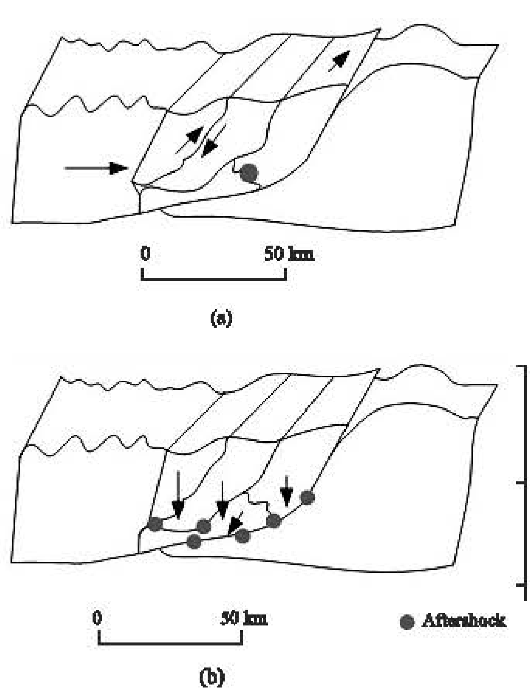

Figure 4 Movement of blocks before (a) and after (b) unloading[14]

(1) The energy of this earthquake came from the joint effect of the Sichuan Basin and the Bayan Har Block, and the Longmenshan fault zone was still dominated by thrusting, which is consistent with the rigid-body displacement in the model; the upper wall was in an upward movement trend, and the lower wall thrust downward, causing overload rupture at the epicenter and thus inducing the earthquake.

(2) The analysis result from Tianquan station in Sichuan, differed greatly from those of other continuous stations; the team led by Prof. Huang Liren from the First Crust Monitoring and Application Center conducted field surveying and determined that this difference is related to the stability of the continuous station and that the data from the continuous station have a low confidence level but their time sequences do not suffer from a major anomaly.

(3) The ES and NW displacements at three continuous stations, i. e., SCYX, SCMN and SCXD, on the north section of the Anninghe fault zone show that the Anninghe fault had some slip movements; the NE displacements at two continuous stations, i. e., CHDU and PIXI in the Sichuan Basin, indicate that the Longmenshan fault zone had a NE slip, and the near-field blocks in the Sichuan Basin had a flow trend along the Longmenshan fault zone after the earthquake occurrence, similar to the fault flow in the model.

The analysis of the data from the continuous stations well supports the assumed model, which has laid a foundation for an in-depth study of the warning-sign mechanisms of earthquakes.

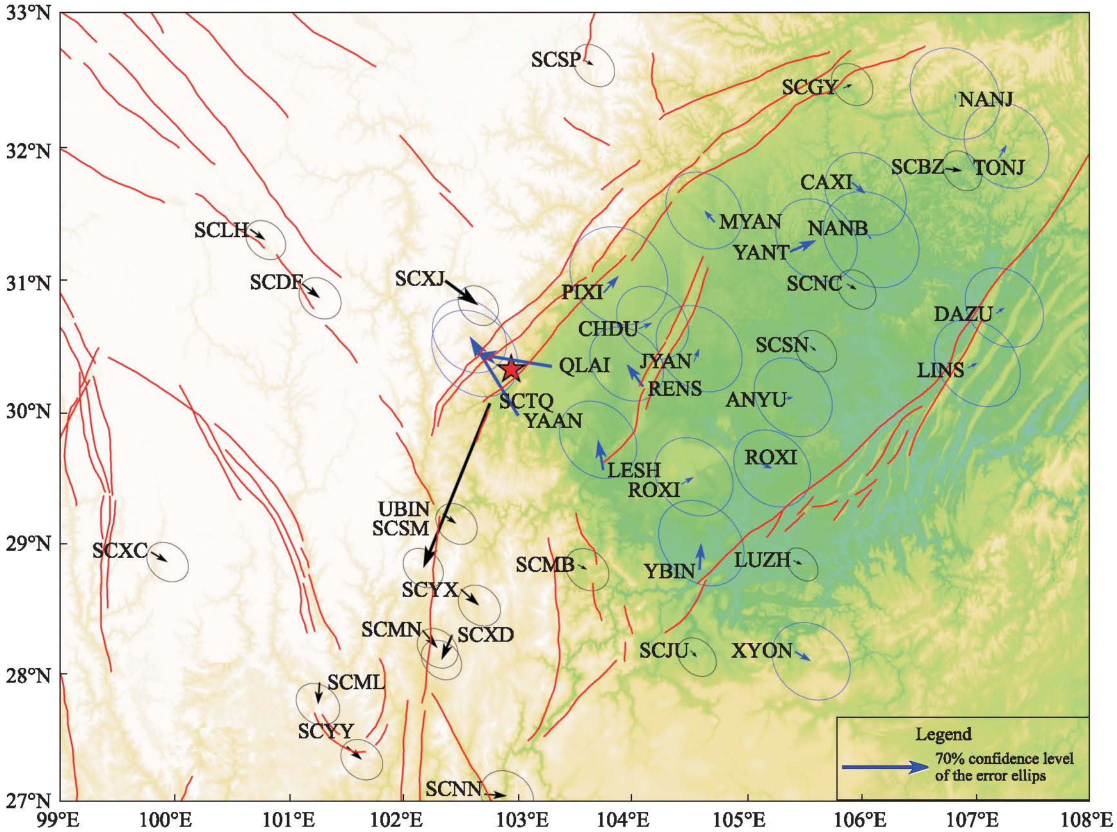

Figure 5 Coseismic displacement map of near-field earthquakes (the red five-pointed star is the epicenter, the black spot is the "Continental Network" GNSS continuous station, and the blue spot is the "Sichuan GPS Observation Network" continuous station)

6 Conclusions

(1) The Lushan earthquake is the result of thrusting activity of the Longmenshan fault zone, its energy comes mainly from the strong compression effect of the Bayan Har Block on the Sichuan Basin, and it may have some relationship to the unloading effect of the Wenchuan earthquake on the Longmenshan fault zone and the northward flow induction of the continuous substances in the Anninghe fault.

(2) With the unloading effect of this earthquake on both upper and lower walls of the Longmenshan fault zone and the breaking degree of the surrounding faults being taken into account, a comprehensive analysis of figures 3 and 5 shows that the block structure in the Longmenshan fault zone has strong fluidity along the fault zone and thus releases energy from the Longmenshan fault zone; therefore, the recurrence possibility of a major earthquake caused by this earthquake is small in this area but attention should be paid to the earthquake-free area between the southwest section of the Longmenshan fault zone and the Wenchuan earthquake location.

(3) Under the continuous pushing by the Qinghai-Tibet Plateau and blocking by the blocks on the northeast, the Bayan Har Block has a greater possibility of slipping toward the Sichuan Basin, compared with the Caidam and Qiangtang Blocks; coupled with the unloading effect of the Yushu earthquake, the Wenchuan earthquake, and the Lushan earthquake, the future possibility of earthquake development will be high in the middle and east sections of the east Kunlun fault zone and between the west end of the Bayan Har Block and Margaichace fault zone.

(4) In summary, monitoring emphasis should be on the following sections in this region in the next five years: The junction between the Xianshuihe fault zone and the southwest section of the Anninghe and Longmenshan fault zones, where the earthquake activity has been relatively strong since the Late Quaternary[16]; The middle and east sections of the east Kunlun fault

zone, where the earthquake activity is strong, and multiple earthquakes at *M*s7. 0 or above have occurred[17] since 1900; The east section of the Margaichace fault zone and the west end of the Bayan Har Block, where the *M*s7. 9 Mani earthquake occurred in 1997.

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