Fault activity characteristics in the northern margin of the Tibetan Plateau before the Menyuan Ms6.4 earthquake

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\textbf{Abstract}
Fault deformation characteristics in the northern margin of the Tibetan Plateau before the Menyuan Ms6.4 earthquake are investigated through time-series and structural geological analysis based on cross-fault observation data from the Qilian Mountain–Haiyuan Fault belt and the West Qinling Fault belt. The results indicate: 1) Group short-term abnormal variations appeared in the Qilian Mountain–Haiyuan Fault belt and the West Qinling Fault belt. The results indicate: 2) More medium and short-term anomalies appear in the middle-eastern segment of the Qilian Mountain Fault belt and the West Qinling Fault belt, suggesting that the faults’ activities are strong in these areas. The faults’ activities in the middle-eastern segment of the Qilian Fault belt result from extensional stress, as before the earthquake, whereas those in the West Qinling Fault belt are mainly compressional. 3) In recent years, moderate-strong earthquakes occurred in both the Kunlun Mountain and the Qilian Mountain Fault belts, and some energy was released. It is possible that the seismicity moved eastward under this regime. Therefore, we should pay attention to the West Qinling Mountain area where an Ms6–7 earthquake could occur in future.

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1. Introduction

According to the China Digital Seismograph Network (CDSN), an Ms6.4 earthquake hit Menyuan Hui Autonomous County, Haibei Tibetan Autonomous Prefecture, Qinghai Province at 1:13 on January 21, 2016. The earthquake’s epicenter was located at 37.68°N, 101.62°E, at a depth of 10 km. The earthquake was called the “Qinghai, Menyuan Ms6.4 earthquake.” Its epicenter was located about 35 km from the Menyuan County and approximately 110 km from Xining; it was strongly sensed in both areas. Before the earthquake, cross-fault monitoring sites in the Qilian Mountain—Haiyuan—West Qinling structural belt where the epicenter was located displayed abnormal responses. The epicenter lies in the Qilian Mountain Fault belt at the northern margin of Tibet Plateau, and the huge extruding force from the collision between the Indian Ocean with the Eurasian Plate provides a major power source for this earthquake. Research on the Quaternary deformation of the northern margin of Tibet Plateau led to the correlation between the genesis of huge crustal deformation and frequent earthquakes in the northern Tibet Plateau [1–6]. Moreover, the northern margin is comprised of multiple plates and blocks, which shapes its complex geological structures. Cross-fault measurement is a real-time, high-precision, and quantified crustal deformation monitoring tool and one of the most direct and effective methods of fault activity monitoring [7–9]. In the present study, we combine cross-fault temporary site data from the northern margin of the Tibet Plateau with seismic tectonic data to analyze the deformation characteristics of regional faults before the Menyuan Ms6.4 earthquake and discuss the high-risk regions for future earthquakes.

2. Regional geology and seismology

The epicenter of the Qinghai, Menyuan Ms6.4 earthquake lies near the Lenglongling Fault in the Qilian Mountain Fault belt. Associated with the subduction of the Indian Ocean Plate under the Eurasian Plate, collision/joining and extruding shaped the very thick Tibet Plateau, i.e., “The Third Pole.” Meanwhile, a series of significant structural belts were formed in the periphery of this large plateau. Massive fault systems were developed between the northern margin of the Tibet Plateau and Alxa block to the north, which include the Qilian Mountain Fault belt [1,2]. This region lies in the collision/joining area of multiple secondary plates and blocks with complicated tectonic attributes; structural lines extend mainly NW–SE, dominated by strike-slip reverse faults (Fig. 1).

The epicenter is close to the Lenglongling Fault, which is a Holocene active fault and reverse-fault and strike-slip. At present, this seismogenic fault is considered a small-scale, buried fault between the Minle–Damaying Fault and the Lenglongling Fault.

Since 1900s, five earthquakes bigger than Ms5 hit within the 100 km range of the epicenter, the largest one was the Gulang Ms8.0 earthquake with an epicenter about 50 km from this earthquake. The Menyuan Ms6.5 earthquake in 1986 was closest (10 km) to this earthquake location. The latest large earthquake was the Qilian Ms5.2 earthquake in 2015.

3. Material and methods

3.1. Cross-fault sites

More than 70 cross-fault sites were selected in the Qilian Mountain—Haiyuan Fault belt and the West Qinling Fault belt in the study area to obtain data for the analysis. The observation sites were built during 1970s–1980s; thus, at least 30 years of complete and continuous observation data were accumulated. Site deformation monitoring mainly adopts short-leveling observation. Moreover, more than ten comprehensive sites covered by infrared baseline distance measurements in the Qilian Mountain Fault belt are found (Fig. 2). This area is mainly under the charge of the Second Crust Monitoring and Application Center of China Earthquake Administration (CEA).
The cycle of short-leveling measurements is 3–5 times per year and that of baseline survey is 1 time per year. In an urgent earthquake situation, intensive observation can be performed. The instrument operates well, following the various technical requirements set by the State Seismological Bureau’s Specifications for Cross-fault Geodetic Measurements. Thus, the observation results have high-precision, with mean square error of the round-trip survey at 0.2 to 0.3 mm. Accordingly, fault activities in the northern North–South seismic belt and in the northern margin of the Tibet Plateau can be precisely and effectively monitored.

3.2. Cross-fault data analysis

Pre-processing was conducted on the massive amounts of deformation data collected from the cross-fault temporary sites in this study. First, we eliminated the abrupt changes aroused by disturbances in the cross-fault observation data and continuously checked the observation data to eliminate repeated data. Then, we filled the data that was missing because measurements were not available in daily observation, using the linear interpolation method to obtain cross-fault deformation measurement data of a uniform observation cycle. For new sites, which contain observation data for a short time only, the site stability needs to be checked; therefore, they were temporally not analyzed. Subsequently, we drew primitive curves by programming with Matlab. Analysis of curves indicates that before the Menyuan earthquake, many cross-fault temporary sites displayed obvious abnormal variations. For example, in the Qilian Mountain–Haiyuan Fault belt, sites with short-term anomalies included Hongliuxia, Xichache, Biandukou, Hexibaotai, Jiutiaoling, Jiling east, Wuqiaoing, Anguozhen, Sanguankou, and Hongbazi; in the West Qinling Fault belt, sites with anomalies included Majiasi, Santiaoba, Jiangkou, Maoji, Luijiagou, Huangjiaba, and Xiakouyi (Fig. 3).

4. Results

The analysis of primitive curves of cross-fault temporary site observation data within the area indicates the following:

1. Before the Menyuan earthquake, the cross-fault temporary sites displayed group abnormal responses. These anomalies can generally be divided into compressional, extensional, short-term compressional-to-extensional and wave anomalies.

(1) Compressional anomalies were recorded after July 2013, when the Hongliuxia level cumulatively decreased by 2.42 mm and the compressional fault activities were intense. In March 2015, the Sanguankou level turned from rising to decreasing in the curve, decreasing by 3.96 mm, with compressional characteristics. Furthermore, the Hongxianzi level started to drop substantially in November 2014 by 2.86 m and slightly rose again recently. The Maoji level started to drop greatly after July 2015 by nearly 3 mm and slightly rose recently with compressional-dominated fault activities. The Luijiagou level dropped rapidly in May 2015 by 1.16 mm in total, and the fault activities displayed compressional characteristics. The Santiaoxian level started to rise at the beginning of 2015 and started to drop in April with accumulative range of 1.19 mm and faulting turned from extensional to compressional. Fig. 2 displays that except for Hongliuxia in the westernmost end, another five measurement sites, Sanguankou, Hongxianzi, Maoji, Luijiagou, and Santiaoxian, are located in the east, demonstrating that the east is dominated by compressional anomalies.

(2) Tensional anomalies include the Xichache level that started to increase abruptly by 1.84 mm from the previously decreasing in the middle of 2015. The Xichache baseline displayed a similar rising trend in recently, and the fault activities were dominated by extension. The Jiling east level rapidly rose by 0.53 mm between July and November 2015, and the fault activities displayed obvious tensional characteristics. The Wuqiaoing level rapidly rose by 0.56 mm after March 2015, and the faulting displayed tensional characteristics. The Anguozhen level displayed a vibrated rise after 2012; the latest data reveals that it rose by 3.62 mm and the faulting activated intensely, revealing tensional movement characteristics. As displayed in Fig. 2, in survey points dominated by tensional activities, Anguozhen is located in the eastern fault; Xichache, Jiling east, and Wuqiaoing lies in the central Qilian Mountain fault belt closer to the epicenter. Accordingly, cross-fault measurement results display that the near-epicenter levels are dominated by tensional movement before the earthquake. In terms of the geological setting, NW-trending faults breed inverse, strike-slip earthquakes and faults that indicate compressive movement. From the perspective of a major dynamical environment, this region was extruded by the Tibet block from the southwest. However, they are now in mutual contradiction, which possibly results from the difference of physical properties between the surface and the deep crust media. Deep crust media displays relatively strong plastic and flow characteristics and is locally uplifted by extrusion in long-term nearly NE-trending stress, resulting into surface faulting displaying extensional, normal fault properties on a small scale and within a short time. This is also similar to the formation of local uplifts and mountains aroused by this long-term mechanism.

(3) Short-time compressional-to-extensional anomalies include the Jiling east baseline, which rose greatly in the early half of 2014; the dropping trend ceased, and fault movement turned from compressional to extensional. The Biandukou baseline stopped decreasing and started to rise after the middle of 2015, and faulting turned from compressional to tensional. The Hexibaotai level, after greatly decreasing by 0.56 mm in 2015, turned to rise recently, and faulting turned from shortening extrusion to extension. The Jiutiaoling level, after dropping by 0.58 mm in 2015, turned to rise and faulting turned from compressional to tensional. Fig. 2 indicates that these sites are closer to the epicenter, indicating large-scale compressional movement and local
Fig. 3 – (To be continued).
Uplifting might be expressed in some of the cross-fault measurement points and showing turning changes before the earthquake.

Wave anomalies include the Majiasi level, which became stable after breaking the historical cyclic change, and faulting weakened possibly due to the geostress increase leading to the closure of the local faulting. The Jiangkou level fluctuated greatly in recent times, with a maximum of 2.24 mm, and faulting activated intensely. The Xiakouyi level similarly indicated a significant increase after 2015 and the faulting frequency was high. Majiasi lies in the east of the Qilian Mountain Fault belt (Fig. 2), close to the North–South belt, whereas the Jiangkou, Huangjiaba, and Xiakouyi cross-fault survey sites are located in the nearly SE-trending South–North belt and in the West Qinling structural belt. The focal mechanism of the Menyuan earthquake indicates sinistral inverse strike slipping, the SW wall of the fault was displaced toward northeast, and energy was released by the NE-trending extrusion. However, due to sinistral movement, the compressive stress shifted eastward locally, possibly resulting into the fluctuated fault activity anomalies in the four aforementioned sites.

2. The different segments of the Qilian Mountain Fault belt show different characteristics. The cross-fault temporary sites in the southwestern segment of Qilian Mountain mostly display tendency anomalies and faulting inherits previous movement characteristics. On the other hand, cross-fault temporary sites in the central eastern segment mostly show rapidly rising and falling, breaking tendency, and other such short-term anomaly characteristics. The latest observation data indicates they started to turn from compressional to tensile movement and recent activities generally show tensional characteristics. The Menyuan Ms 6.4 earthquake resulted from the turning of...
faulting, showing a good correspondence. In the Haiyuan–Liupan Mountain Fault belt, the monitoring data for the cross-fault sites indicates that fault activities in the Liupan Mountain Fault belt are more intense than in the Haiyuan Fault belt. Cross-fault sites in the West Qinling Fault belt displayed group abnormal responses and mostly great fluctuation, cusp jump, and other short-term anomaly characteristics. The faults are generally dominated by compressional movement. Different segments show different fault activities, which are correlated to the fault occurrence, the dynamic environment, and the fault's relative location to the epicenter. Moreover, these prove the complex regional tectonic regime in the study area.

3. Analysis of the entire West Qinling-Qilian Mountain structural belt indicates that there are many site anomalies and significant compressional anomalies in the central eastern segment of Qilian Mountain Fault belt and the West Qinling Fault belt. Anomalies in the Qilian belt can reasonably be associated to this Menyuan earthquake, whereas group anomalies in the west Qinling belt, due to the greater distance from the epicenter, correspond to different structural activities and intensities, which are difficult to interpret in relation to the Menyuan earthquake. Considering that the compressive-shear seismogenic mechanism of the Menyuan earthquake favors the eastward movement of compressive stress field, the central eastern segment of Qilian Mountain Fault belt and the West Qinling Fault belt should be closely monitored and traced.

5. Discussion and conclusions

Based on the analysis of huge amount of observation data obtained from the cross-fault temporary sites in the Qilian Mountain–Haiyuan Fault belt and in the west Qinling Fault belt in the northern margin of the Tibet Plateau, it is believed that, before the Menyuan Ms6.4 earthquake, the crustal movement intensified in this area. Most research results indicated that large-scale crustal vertical and horizontal deformation took place in this area in recent years, which accumulated an extremely high amount of stress and created a moderate to strong earthquake-preparing setting [10,11]. Compared to the Minle Ms6.1 and the Minxian—Zhangxian Ms6.6 earthquakes, the Qilian Mountain Fault exhibited more anomalies and displayed signatures of anomaly sites moving toward the central eastern segment of the Qilian Mountain belt in the case of the Menyuan Ms6.4 earthquake. The velocity field of the Qilian Mountain block obtained by GPS shows a turning from N to NE, suggesting that regional sinistral strike-slip movement continuously intensified [12]. As such, with the Indian Ocean Plate continuously subducting and extruding toward the Eurasian plate, various blocks within the Tibet Plateau correspondently adjusted and interacted. In the northern margin of the Tibet Plateau, a series of EW–NW trending faults among blocks within the plateau, the Alxa Block and the North China Plate, suffered from thrusting and strike-slip movements, and generated significant stress in specific structural positions. This dynamic setting led to the Menyuan earthquake.

According to historical earthquake research, large amounts of cusp and jump cross-fault site anomalies appeared near the Liupan Mountain and the west Qinling Fault belts; the central eastern segment of the Qilian Mountain Fault belt in the northern margin of Tibet Plateau commonly possesses a high-risk of moderate to strong earthquake occurrence [13–15]. Consequently, the movements and variations of these main fault belts are in correlation and interaction, particularly before moderate to strong earthquakes take place. The Menyuan Ms6.4 earthquake occurred in the central eastern segment of the Qilian Mountain Fault belt. The west Qinling and the Liupan Mountain Fault belts further from this belt displayed large amounts of short-term anomalies. On the contrary, many medium to short-term anomalies appeared in the Qilian Mountain Fault belt, and we do not exclude the possibility of moderate to strong earthquakes hitting the west Qinling Fault belt in the future. Meanwhile, as part of the Qinling–Qilian–Kunlun large structural belt, moderate to strong earthquakes have hit the Kunlun Mountain and Qilian Mountain Fault belts, releasing accumulated energy to a certain degree and increasing the possibility of seismic activity moving eastward. The Menyuan earthquake shows signatures of sinistral strike-slip movement, which also favors the increased nearly EW-trending compressive stress in the east. There are possibly more compressive anomalies in the east; thus, attention should be paid to the east and west Qinling area.

Accordingly, the present study leads to the following conclusions:

1. Before the Qinghai, Menyuan Ms6.4 earthquake, the cross-fault sites indicated group short-term anomaly responses in the Qilian Mountain Fault belt, eastward extending to the Haiyuan–Liupan Mountain Fault belt, even to the west Qinling Fault belt.

2. Based on the distribution of the cross-fault temporary sites with anomalies present, there are many medium to short-term anomalies and faulting was intense in the central eastern segment of the Qilian Mountain Fault belt and in the west Qinling Fault belt. In the central eastern segment of the Qilian Mountain Fault belt, fault activities displayed tensional characteristics before this earthquake occurred and the west Qinling Fault belt was generally dominated by thrusting activities.

3. In recent years, both the Kunlun Mountain and the Qilian Mountain Fault belts were hit by moderate to strong earthquakes, where accumulated energy by the faults were thus released to a certain degree and possibly the seismic activity increased eastward. Accordingly, attention should be paid to the risk of Ms6–7 earthquakes in the west Qinling area in the future.

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