Recent crustal movement and great earthquakes in Qinghai-Tibet sub-plate

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Abstract: Crustal movement and incremental-movement data observed repeatedly at GPS stations during 1999-2009 were analyzed to study the effect of two earthquakes of Ms8.1 and Ms8.0 that occurred in 2001 and 2008, respectively, in Qinghai-Tibet sub-plate and its eastern margin. The result revealed certain anomalous pre-earthquake deformation and some large co-seismic changes. Prior to the 2008 Wenchuan Ms8.0 earthquake, the seismogenic Kunlunshan fault zone became a geographic boundary between different regional movements. At the time of the earthquake, there was an average cross-fault crustal shortening of $-1.04$ m and an average right-lateral strike slip of $0.76$ m along the ruptured segment, as well as a strain-energy release of $-62.66 \times 10^7$.

Key words: Qinghai-Tibet sub-plate’s movement field; tectonic activity; movement incremental field; earthquake deformation; strain energy; Wenchuan earthquake

1 Introduction

Two $Ms \geq 8$ earthquakes ($Ms8.1$ to the west of the Kunlun Mountain Pass on 2001-11-14; Wenchuan Ms8.0 on 2008-05-12) occurred during the past decade in the Chinese mainland, and they both were located in or bordering the Qinghai-Tibet sub-plate, which is the southern part of the Eurasian-Tibet sub-plate, which is the southern part of the Eurasian plate. To study the characteristics of current crustal-movement field and tectonic activity in this currently most active region in Chinese mainland has important practical significance on disaster reduction and earthquake prediction. A large network of GPS stations has been constructed and in operation since 1999, and repeated measurements were carried out in 2001, 2004, 2007 and 2009. The accumulated large amount of data has been used by experts to study the deformation and the earthquake-related movements in this region.$^{[1-5]}$. In this paper, we report on an analysis of the incremental movements and earthquake-related deformations in the Qinghai-Tibet sub-plate, based on results of the multi-stage GPS observations.

2 Methods

Previous studies on earthquake tectonics showed that most $Ms \geq 7$ earthquakes were located in fault zones bordering class I and II active blocks. This fact illustrates that the development of great earthquakes is the result of block activities, or a process of energy accumulation and release in the earth’s crustal-block interaction. Therefore, when analyzing seismicity and crustal deformation, we should try to capture information of anomalous changes on a scale comparable to the corresponding blocks. Also in GPS deformation studies, significant results have been obtained through calculation and analysis with block-movement models, which high-
lighted the deformation of the blocks, rather than smaller local changes. The following analysis is mainly based on the result of calculation, using a linear-elastic-block-motion model expressed by \( (1) \):

\[
\mathbf{v} = \begin{bmatrix} v_x \\ v_y \end{bmatrix} = \begin{bmatrix} -\sin \phi \cos \psi - \sin \phi \sin \psi \\ -\cos \phi \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \end{bmatrix} + \begin{bmatrix} A_0 \\ B_0 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \frac{1}{2} \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix} \begin{bmatrix} x^2 \\ y^2 \end{bmatrix} + \begin{bmatrix} \xi_3 \end{bmatrix} \begin{bmatrix} xy \end{bmatrix}
\]

where \( \omega_x, \omega_y, \omega_z \) are block-rotation parameters, and \( A_0, B_0, C_0, \xi_1, \xi_2, \xi_3 \) are strain parameters.

Equation (1) shows that the block movement consists of two parts, an overall rotation and internal deformation. Following is a description of our result of applying this model to the analysis of current activity of Qinghai-Tibet sub-plate.

3 The overall-movement field

We obtained the overall-movement field in the sub-plate during 1999-2009 (Fig. 1) by subtracting the overall rotation parameters from the observed site velocities in the global framework, using the calculated results of the GPS measurements during this period. From figure 1 we see that the velocity was greater in the southwestern and the southern part, and gradually decreased towards north and east to a minimum in Qaidam-Western Qinling region. The movement field in the central and southern parts showed a clockwise rotation around the Assam tectonic node, west of which the movement direction gradually changed from NNW to N and NE direction, while north of the node the movement was in east direction. In the eastern part, from north to south, the direction gradually changed from the southeast to south and southwest. In the northern part, in Qilian Mountain and areas near the Altun fault, the direction turned northwest.

North of the South Qilianshan fault the region was in northwest movement, while on the south side of the fault the Qaidam-West Qinling block was moving northward, indicating a left-lateral movement of the fault. The same tendency was shown for the Kunlunshan fault zone, the north side of which moved northward while the south side moved northeastward. The velocity on the north side of Hoh Xil-Yushu-Xianshuihe fault zone was slower than the south side, indicating that the western segment of the fault zone had a tendency of compression, while the eastern segment a tendency of left-lateral movement. The eastward movement of the northern side of Bangong Lake-Jiali fault was faster than the southern side, so the fault showed a tendency of right-lateral movement.

![Figure 1 Movement field of Qinghai-Tibet sub-plate(1999-2009, non-rotational datum)](image)
Thus the overall movement field of the Qinghai-Tibet sub-plate may be divided into two parts according to the changes in speed and the direction: the Qaidam-Qilian Mountains-West Qinling in the north and the Hoh Xil-BayanHar block, the Qiangtang-Sichuan Yunnan block and the Gangdise-Lhasa block in the south. They are bordered by Kunlunshan fault zone, which is manifested as a notable structure of the sub-plate currently.

4 Incremental movements

To examine the horizontal deformation at different observation stages, we show in the following figures the incremental velocity changes (the velocity of the later time period minus the velocity of the previous time period), which directly reflects the deformation in different periods: (2001 – 2004) minus (1999 – 2001), (2004 – 2007) minus (2001 – 2004), and (2007 – 2009) minus (2004 – 2007). In the following discussion, we divided the sub-plate into Qaidam-Qilian Mountains-West Qinling, Qiangtang-Sichuan-Yunnan, the Hoh Xil-Bayan Har, and Gangdise-Lhasa blocks (numbered 1 – 4, respectively, in the following figures).

Figure 2 shows the incremental field of (2001 – 2004) minus (1999 – 2001), which should reflect the changes related to the Ms8.1 earthquake on November 14, 2001 to the west of the Kunlun Mountain Pass, because it occurred in between the two sets of observations. From figure 2 we see that in the north the main part of Qaidam-Qilian Mountains-the West Qinling block moved to west, with the maximum velocity occurring in the southern margin near the Kunlunshan fault zone, the northwestern edge near the Altun fault zone moved southward. While the part east of Lanzhou moved eastward, thus resulting a tension in the Tianzhu-Wudu area.

The vast region of the central part of the Hoh Xil-Bayan Har block (81° E to Yushu-Norgay) adjacent to the southern part of Qaidam-Qilian Mountains-West Qinling block moved to the east and south, with maximum velocity occurring near the the Kunlunshan fault to the north. The area west to 81° E moved northwestern with a small velocity. The region east to Yushu-Norgay line moved to the west, forming a compression zone in the Yushu-Norgay areas. The north and south sides of Kunlunshan fault zone moved left-laterally at a relatively large speed, indicating an obvious relation with the Ms8.1 earthquake.

The part of Qiangtang-Sichuan-Yunnan block west of 96° E moved toward EEW, while the eastern part gradually turned to the east. The velocity was significantly smaller than the two blocks mentioned above. The movement direction of the middle section of the northern boundary of the block was consistent with that of the Hoh Xil North-Bayan Har block, while the directions in the mid-eastern section were quite different, or even opposite.
The Gangdise-Lhasa block moved slowly to the SEE, like the Qiangtang-Sichuan-Yunnan block to the north, showing a lack of activity at their boundary fault zone, Bangong-Jiali.

To sum up the velocity increments of (2001 – 2004) minus (1999 – 2001), the maximum occurred along a 1400 km segment of the Kunlunshan fault zone between 85° and 100° E, probably related to the Ms8.1 earthquake. Two areas in the eastern section of the Qaidam-Qilian Mountains-West Qinling and the Hoh Xil-Bayan Har blocks showed differential deformation; tension in Tianzhu-Wudu and compression in Yushu-Norgay. Farther from the earthquake, the Qiangtang-Sichuan-Yunnan and Gangdise-Lhasa blocks showed consistency in the movement directions. The incremental-movement field during this period may be divided into four areas: Qaidam-Qilian Mountains north of Kunlunshan fault zone moved to the west, Hoh Xil-Lhasa to the south moved to the east. West Qinling in the northeast of the sub-plate moved to the east, and Longmen Mountain in the south to the west.

The incremental-movement field of (2004 – 2007) minus (2001 – 2004) is shown in figure 3. The movement direction of the western part of the Gangdise-Lhasa, Qiangtang-Sichuan-Yunnan, and Hoh Xil-Bayan Har blocks turned from north in the south into the northwestern the north, while the central part consistently moved to the north with no significant differences at the block boundaries. The incremental velocity of the Gangdise-Lhasa block was the largest, and that of the Hoh Xil-Bayan Har block smallest. In the eastern part of Hoh Xil-Bayan Har and Qiangtang-Sichuan-Yunnan blocks the movement direction was south to southwest, and locally east-west. In the Qaidam-Qilian Mountains-West Qinling block, the mid-western part moved to the northeast, while the eastern part moved to the south and southwest. The velocity increment was relatively large in the mid-western part, and was minimum in the eastern Weiyuan-Longxi region. Generally speaking, the movement of the eastern region centered at Lanzhou-Songpan-Julong was very different from that of the mid-western regions, with direction towards south-southwest rather than east-northeast.

Thus the incremental-movement field during this period may be divided into two parts: the northward-moving mid-western area and the eastern West Qinling-Longmen-Sichuan and Yunnan area. The field was not affected by block boundaries, except a small effect of Kunlunshan fault zone.

Figure 4 shows the incremental-movement field of (2007 – 2009) minus (2004 – 2007), which included the changes related to the Wenchuan earthquake on May 12, 2008. The earthquake caused the eastern part of the Hoh Xil-Bayan Har block to move towards E and NEE, at a large speed, and the eastern part of the Qaidam-Qilian Mountains-West Qinling block to move towards NEE and NE, dragging the middle-western part of these blocks towards SE.
During this period, the western end of the Qiangtang-Sichuan-Yunnan block moved to the northwest, the central part to the southeast, and the southeastern part to the east-northeast. In the Yushu-Yaan segment, the eastward movement of the Hoh Xil-Bayan Har block in the north was faster than the Qiangtang-Sichuan-Yunnan block in the south, indicating a right-lateral movement at the boundary fault. In the Gangdise-Lhasa block, the eastern part moved to the south, the central part to the west, and the western part to the north-west. As a whole, during this period the incremental movement was distinctly multi-directional, being affected by the Wenchuan earthquake, which was associated with a significant incremental movement along Longmenshan fault zone at the eastern boundary of the Hoh Xil-Bayan Har block; the range of influence was about 590 km.

The main feature of the incremental-movement field during this period was two areas of clockwise rotation divided by the Hoh Xil-Yushu fault zone; one centered at middle section of Qilian Mountains in the north; the other centered at Gaize region in the south.

The above-described results indicate that crustal movement showed significant changes at times of earthquake occurrence, and for Ms8 and larger earthquakes the affected fault zones were as long as several hundred to a thousand kilometers. Also significant differential changes appeared in the incremental-movement fields of the involved blocks (Fig. 2, Fig. 4). In addition, before the great earthquakes there were abnormal movements in regions associated with the earthquakes (Fig. 3). In other word, the incremental-movement fields changed significantly with the development and occurrence of great earthquakes.

5 Earthquake-related changes along the Longmenshan fault zone

At the time of Wenchuan earthquake, significant offset occurred along the Longmenshan fault zone, releasing an enormous amount of strain energy (Figs. 5 and 6). From inverse calculation of the data from GPS sites distributed in different blocks, we obtained an average crustal shortening across the ruptured section of -1.04 m, and an average right-lateral strike slip of 0.76 m. The largest shortening was -1.38 m, and right-lateral strike slip was 0.94 m (Fig. 5).

The corresponding average principal compressive strain was $-62.66 \times 10^{-7}$ with, principal axis (P) in SE110.5° direction, the average principal tensile strain was $55.26 \times 10^{-7}$ with axis (T) in NE, the maximum shear strain was $117.62 \times 10^{-7}$, and the plane strain was $-57.00 \times 10^{-7}$. Along the fault zone, the maximum earthquake-related main compressive strain was $-162.23 \times 10^{-7}$, the maximum tensile strain was $59.36 \times 10^{-7}$, and the normal strain was $-57.00 \times 10^{-7}$ (Fig. 6).
6 Conclusion

(1) During the study period of 1999–2009, the crustal velocity in the southwestern part of the sub-plate was larger than the northern part, Qaidam-West Qinling. The currently active Kunlunshan fault zone divided the sub-plate into two parts; the northern part of Qaidam-Qilian Mountains-West Qinling block moved to the northwest, while the southern part, Hoh Xil-Bayan Har block, Qiangtang-Sichuan-Yunnan block and the west part of the Gangdise-Lhasa block, moved to the north and northwest; Assam tectonic node in the mid-east underwent a clockwise rotation.

Regarding earthquake activity in the sub-plate, since 2000 four large events occurred around the Hoh Xil-Bayan Har block boundary fault zone: Yutian Ms7.3 (2008–03–21) along the Kunlunshan fault, Ms8.1 west of the Kunlun Mountains Pass (2001–11–14), Wenchuan Ms8.0 (2008–05–12) in the Longmenshan fault zone, and Yushu Ms7.1 (2010–04–14) in the Hoh Xil-Yushu fault zone. No Ms ≥ 7.0 earthquake occurred in any other blocks in the sub-plate. Thus, as a class II block boundary, the Kunlunshan fault zone showed the strongest activity, both seismically and tectonically during 1999–2009.

(2) The ranges of crustal movements associated with the Ms8.1 (2001–11–14) and Ms8.0 (2008–05–12) earthquakes were over a thousand kilometer and 590 km, respectively. The two sides of Kunlunshan fault zone moved in the opposite directions. The ruptured segment experienced an average shortening of more than 1 m in the cross-fault direction (mainly due to E-NEE movement of the west side, Fig. 5) and an average strike slip of 0.76 m.

(3) The main compressive strain released by Wenchuan earthquake along the ruptured segment of Longmenshan fault zone was \(-162.23 \times 10^{-7}\) (maximum) and \(-62.66 \times 10^{-7}\) (average).

(4) The incremental-movement changes in the blocks revealed some mid- and long-term anomalies before the large earthquakes. Before Wenchuan earthquake, the incremental field of (2004–2007) minus (2001–2004), in western Qinling and Longmenshan and its western neighborhood were abnormally different from that of the vast mid-western region of the sub-plate, forming a system by itself with a relatively small speed and a significantly different direction.

References


