Research on Recent GPS Crustal Deformation Characteristics in the Northeastern Edge of Qinghai-Tibet Plateau

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Abstract. Based on the GPS data in the northeastern edge of Qinghai-Tibet Plateau, the velocity field and the extension change rate of baseline between stations are analyzed. The crustal movement characteristics and their dynamic changes in this region are discussed. The result indicates that the baseline in the regions demonstrates an overall characteristic of shrinking in the NE direction and extending in the NW direction; The extrusion of Bayan Har Block in SE direction since 2009 has amplified obviously, which leads to the enhancement of correlated movement in SE direction in the NW side of Longmenshan Fault. In addition, Tianzhu empty regions and the area near the epicenter of Menyuan Ms6.4 earthquake in 2016 are right in the boundary of this differentiated movement. Recently, a certain amount of strain energy might have been accumulated in the nearby area of the northern margin of Alkin Fault Zone, west boundary of Erdos Block and west to105°N on Northern Xiqinling Fault. The seismic risk in the west and east section of the intersecting area between Bayan Har Block and Qaidam Block is high. The west section of Northern Xiqinling Fault belongs to the inner ring of clockwise vortex and possesses medium-strong seismic risk.

1. Introduction
The northeastern edge of Qinghai-Tibet Plateau is where the Tibet Block, Alxa Block and Erdos Block converge[1]. Considering that it is located in the drastically-uplifting frontier part in the northeastern Qinghai-Tibet Plateau, this region becomes one of the zones where the structural activities are the most active and the seismic activities are the most frequent in Qinghai-Tibet Plateau. In this region, active fault zones, such as Qilian Mountain, Haiyuan Fault, Liupanshan, northern fault zone of West Qinling Mountain, have been developed from north to south since the Neotectonic era. Driven by the main active force by northward extrusion and impact onto the Eurasia Continent by the Indian Plate, and blocked by the rigid Alxa Block and Erdos Block, the characteristics of geological structural activities in the active fault zone in the northeastern edge of Qinghai-Tibet Plateau are mainly demonstrated as NE extrusion-thrust and sinistral strike slip-rotation [2]. Huining Ms7.0 earthquake in 1352, Zhongwei Ms7.2 earthquake in 1561, Guyuan Ms7.0 earthquake in 1622, Tianshui South Ms8.0 earthquake in 1654, Zhongwei Ms7.5 earthquake in 1709, Yinchuan-Pingluo Ms8 earthquake in 1739, Wudu Ms8 earthquake in 1879, Haiyuan Ms8.5 earthquake in 1920, Gulang Ms8 earthquake in 1927 and over ten M6–6.9 earthquakes occurred in this region[3, 4], and thus this region is equipped with strong seismic development background.

Earthquake results from the sudden release of all the long-term accumulated strain during crustal movement[5]. The energy for earthquake preparation comes from the accumulation of strain energy...
generated in crustal movement process under the impact of structural boundary dynamic force [6]. Considering that GPS observation can provide the relative movement information in multiple spatial dimensions, applying these observation results into the research of relation between temporal-spatial distribution dynamics of crustal movement and strong earthquakes as well as the seismic deformation process and mechanism might become a vital aspect for seismic forecasting research to expand into physical forecasting. Generally, strong earthquakes occur in the regions where the crustal movement differs greatly. In other words, strong earthquakes take place in the regions where the magnitude and direction of movement velocity vector differ greatly. Strain can only be accumulated when there is difference in crustal movement. When the regional crustal movement is consistent, no strain will be accumulated, the risk of strong earthquakes is not high [7]. In this paper, based on the GPS mobile observation data in the northeastern edge of Qinghai-Tibet Plateau between 1999 and 2015, the velocity field in the research region is analyzed; then, the GPS continuous observation data since 2010 are utilized to analyze the extension change rate of baseline between stations; next, the current crustal movement characteristics and their dynamic changes in this region are studied. The research result can offer reference basis for the forecasting of strong seismic risks in this region.

2. Velocity Field Characteristics Based on GPS Mobile Observation

The GPS observation data collected in multiple periods since 1999 are processed by GAMIT/GLOBK software and QOCA software [8, 9] to obtain the GPS velocity field 1999-2007 year, 2009-2013 year and 2013-2015 year. The specific processing strategy can refer to literature [10]. On the basis of ITRF2005 reference framework velocity field result, the stable South China Block is adopted as the reference datum and then transformed. Fig.1 presents the comparison result of the velocity field in above three periods.

Based on Figure 1, under the extrusion impact of Indian Plate and certain blockade impact of relatively stable Alxa Block and Erdos Block, the fault zone extending from the north boundary of Qilian Block to Haiyuan the NWW direction demonstrates obvious sinistral strike-slip and extrusion differentiated movement characteristics. In other words, the north of this fault zone demonstrates W-NWW movement while the south demonstrates NE-E-ES movement. The velocity field in the region ranging between 36°N and 42°N, between 94°E and 100°E, forms a counterclockwise vortex across different geological structural elements, and the direction of its movement vector is shown as NE-near NS-NW direction on the whole from its south to its north, and demonstrates counterclockwise rotation trend. The region surrounding by north to 34°N, east to 100°E, the north boundary of Qilian Block, Haiyuan Fault and Liupanshan Fault forms a clockwise vortex across different geological structural elements, and the direction of its movement vector is shown as NE-near EW-SE-S direction on the whole from its west to its east, and demonstrates clockwise rotation trend. In the area near the block boundary and active fault controlled by vortex movement, the abnormal crustal deformation zone is where the crustal movement velocity is very high or the magnitude and direction of two adjacent observation stations differ obviously [11]. The direction of velocity vector on both sides of the north boundary of Qilian Block-Haiyuan Fault-Liupanshan Fault differs greatly. These are the actively-moving faults in Neotectonic ear and the major seismic activity zones. Considering that the north boundary of Qilian Block and the west boundary of Erdos Block are extruded, the velocity on their NE side is small. The velocity of Bayan Har Block is obviously larger than that of other areas in the research region.

In Fig.1, the black arrow represents the velocity field result 1999-2007 year in the northeastern edge of Qinghai-Tibet Plateau (observed before Wenchuan Ms8.0 earthquake). This period is not influenced by the Wenchuan Ms8.0 earthquake. Therefore, the velocity field in this period can be adopted as the basic movement deformation background field in a relative sense in the northeastern edge of Qinghai-Tibet Plateau while the velocity fields in the later periods serve as the dynamic fields. It can be known from Fig.1 that the direction of the movement vector in the east of Bayan Har Block turns from NEE and EW directions 1999-2007 year to EW and SE directions 2009-2013 year and 2013-2015 year, and the velocity increases obviously, which indicates that the extrusion of Bayan Har Block in SE direction since 2009 has amplified obviously and reflects that the Wenchuan Ms8.0 earthquake leads to the Longmenshan Fault unlocking in a wide range, causing the enhancement of
correlated movement in SE direction in the NW side of Longmenshan Fault. In the three velocity fields, the magnitude and direction of velocity vector on both sides of the west section of the intersecting area between Bayan Har Block and Qaidam Block differ, and the vector direction is NS in the north and NEE in the south, and the velocity in the south is obviously larger than that in the north; compared to the velocity field 1999-2007 year, the difference between the velocity magnitudes on both sides of the east section of the intersecting area between Bayan Har Block and Qaidam Block 2009-2013 year and 2013-2015 year is enlarged, and the velocity increase in the south is obviously larger than that in the north; in addition, the movement vectors on both sides differ, NE direction in the north but EW and SE directions in the south.

![Figure 1. Results of GPS velocity field in the study area (South China Datum). (Black arrow represents 1999-2007 year, red arrow represents 2009-2013 year, blue arrow represents 2013-2015 year, HYF represents Haiyuan Fault, LPSF represents Liupanshan Fault, XQLBYF represents Northern Xiqinling Fault)](image)

In the mid-west Qilian Block, the direction of velocity vector is demonstrated as near NS direction on the whole 1999-2007 year and 2009-2013 year. 2013-2015 year, the direction of velocity vector changes obviously and is demonstrated as NNE direction on the whole, which enlarges the difference between the movement directions of mid-west Qilian Block and its northern regions. In the three velocity fields, the movement direction of east Qilian Block is NE direction and the movement direction on its NE side is NWW direction. In addition, in the velocity field 2013-2015 year, the velocity magnitude in the east Qilian Block obviously increases, which indicates that the magnitude and direction of velocity vector on both sides of the east section in the north boundary of Qilian Block differ greatly. It is shown by research that strong earthquakes occur in the regions where the magnitude and direction of movement velocity vector differ greatly. Strain can only be accumulated when there is difference in crustal movement. Tianzhu empty and the area near the epicenter of Menyuan Ms6.4 earthquake on January 21st, 2016 are right in the outer ring of the clockwise vortex, and the movements on both sides differ greatly, and thus they are where the strain is accumulated.

The movement directions on both sides of the west section of Haiyuan Fault Zone are opposite, namely W direction in the north side and E direction in the south side. The difference in the directions of velocity fields on both sides of the east section of Haiyuan Fault Zone obviously attenuates 2013-2015 year, and the velocity direction on the north side turns from W direction in the previous two periods to SW direction 2013-2015 year. Haiyuan Fault Zone is the sinistral strike-slip fault zone. In the velocity field 2013-2015 year, the velocity direction in the large area on NE side changes into extrusion movement relatively perpendicular to the fault zone. This might be the cause for the velocity increase on the SW side. When the regional crustal movement is consistent, no strain will be
accumulated and the risk of strong earthquakes is not high, which indicates that the current risk of strong earthquake in the east section of Haiyuan Fault Zone is low.

Compared to the previous two periods, the 2013-2015 year movement velocity on both sides of the section west to 105°N on Northern Xiqinling Fault differs greatly, larger on the south side and smaller on the north side. This area is in the inner ring of the clockwise vortex, and the direction turns from near EW direction to SE direction. This area is where the strain is accumulated and has the possibility of earthquakes.

It is shown by the velocity field in three periods that the direction of velocity vector on both sides of the north boundary of Qilian Block-Haiyuan Fault-Liupanshan Fault differs greatly, and these are the actively-moving faults in Neotectonic era; the velocity field in the region ranging between 36°N and 42°N, between 94°E and 100°E, forms a counterclockwise vortex across different geological structural elements; the region surrounding by north to 34°N, east to 100°E, the north boundary of Qilian Block, Haiyuan Fault and Liupanshan Fault forms a clockwise vortex across different geological structural elements. The extrusion of Bayan Har Block in SE direction since 2009 has amplified obviously, which reflects that the Wenchuan M8.0 earthquake leads to the Longmenshan Fault unlocking in a wide range, causing the enhancement of correlated movement in SE direction in the NW side of Longmenshan Fault. The magnitude and direction of velocity vector on both sides of the west section of the intersecting area between Bayan Har Block and Qaidam Block differ to a certain extent, and the difference between the movement velocity magnitudes on both sides of the east section enlarges, and the movement vectors differ as well. The difference between the movement directions of mid-west Qilian Block and its northern regions enlarges, and the magnitude and direction of velocity vector on both sides of the east section in the north boundary of Qilian Block differ greatly. In addition, Tianzhu empty and the area near the epicenter of Menyuan M6.4 earthquake on January 21st, 2016 are right in the boundary of this differentiated movement. The movement directions on both sides of the west section of Haiyuan Fault Zone are opposite. In recent periods, the movement velocity magnitude on both sides of Northern Xiqinling Fault ranging between 103.5°N-105°N differs greatly.

3. Time sequential movement characteristics of GPS baseline

GPS observation is divided into mobile observation and continuous observation. The mobile observation can guarantee the spatial resolution of the crustal deformation research while the continuous observation compensates for the insufficient time resolution in mobile measurement network and can objectively reflect the time dynamic process of crustal deformation. GPS baseline time-series between stations is basically not influenced by the reference datum and can directly reflect the extension of crustal structure on the line between two stations, namely the dynamic change in relative movement between two stations. In this paper, the data from GPS continuous observation stations collected in the construction of China Continental Structural Environmental Monitoring Network Project since 2010 are utilized to analyze the characteristics of baseline movement velocity of 48 GPS baselines in the northeastern edge of Qinghai-Tibet Plateau in recent seven years. Fig.2 shows the calculation results of extension change rate of baselines between GPS stations in the northeastern edge of Qinghai-Tibet Plateau, in which the red line represents that the baseline is shortening, the blue line represents that the baseline is extends, and the line thickness represents the magnitude of extension deformation. Table 1 presents the statistical results of GPS baseline movement velocity in the research region corresponding to Figure 2, in which the positive velocity represents that the baseline is extended and the negative velocity represents that the baseline is shortened.

It can be known from Figure 2 and Table 1 that the baseline extension change rate in the northeastern edge of Qinghai-Tibet Plateau demonstrates the overall characteristic of shortening in NE direction and extending in NW direction. The baselines NMEJ-NMAY, YANC-GSPL and GSWD-SNTB are the inner baselines of Alxa Block, Erdos Block and South China Block respectively, and the movement velocities are respectively 0.24±0.01 mm/a, -0.07±0.02 mm/a and -0.69±0.02 mm/a, which indicates that the crustal deformation rate inside the three rigid blocks is very small.

The baselines QHGE-QHMD, QHMD-QHMQ and QHMQ-GSMA are respectively located in the west, middle and east section of the intersecting area between Bayan Har Block and Qaidam Block, and their movement velocities are respectively 8.43±0.02 mm/a, -2.84±0.01 mm/a and -0.13±0.01
mm/a. Specifically, the baseline QHGE-QHMD in the west section is extended. In combination of Figure 1, the directions of velocity vector on both sides in the west section differ, N direction on the north side and NEE direction on the south side, which further indicates that the deformation characteristic in this region is extension deformation, and the movement velocity on both sides differ greatly. In addition, the extension rate of this baseline is the largest among the 48 baselines, which indicates that its sinistral strike-slip is the largest and thus the strain accumulation effect in this region is the most obvious. In the middle section, the baseline QHMD-QHMQ is shortening. In combination of Figure 1, the magnitude and direction of velocity vector on both sides in the middle section differ slightly. In the east section, the baseline QHMQ-GSMA has a relatively smaller shortening rate. In combination of the velocity field results in the last two periods, the velocity magnitude on both sides of the east section differs obviously, which indicates that the strain accumulation rate in the east section in recent years has slowed down.

Figure 2. Shrinkage ratio of GPS station baseline in the study area. (AEJBYF represents the northern margin of Alkin Fault, XQLBYF represents Northern Xiqinling Fault)

The movement velocities of baselines GSAX-GSJJY and GSDH-GSJJY crossing the northern margin of Alkin Fault Zone are respectively 0.4±0.01 mm/a and 0.8±0.01mm/a, which indicates that the sinistral strike-slip movement in the northern margin of Alkin Fault Zone is relatively weak, and a certain amount of strain might exist. The movement velocities of baselines YANC-NMWH, YANC-NXZW and YANC-GSJJN in the west boundary of Erdos Block are respectively -0.66±0.02 mm/a, -0.61±0.01 mm/a and -0.73±0.02 mm/a, which indicates that the shortening movement on both sides of the west boundary of Erdos Block is relatively small and a certain amount of strain might have been accumulated. In addition, under the blockade of Alxa Block and Erdos Block, the movement in NE direction in the northeastern edge of Qinghai-Tibet Plateau turns to S direction (the baselines QHGC-QHQL and QHGC-QHMQ in NS direction west to the Longzhong Basin Structure are shortening). Therefore, the baselines GSDX-GSJT, NXZW-GSJJN and GSJD-GSLX in NS direction inside the Longzhong Basin Structure close to the west boundary of Erdos Block are extending.

The movement velocities of baselines GSMX-GSDX, GSJD-GSJJN and GSJD-GSLX crossing Northern Xiqinling Fault are respectively -1.09±0.01 mm/a, -0.54±0.02 mm/a and 1.03±0.02mm/a, which indicates that the mutual movement on both sides of this fault zone in recent years has attenuated, and a certain amount of strain energy might have been accumulated in nearby regions. In the meanwhile, the discussion result on velocity field in Fig.1 further illustrates that the movement
velocity on both sides of the west section of Northern Xiqinling Fault differs greatly. In addition, this region belongs to the inner ring of clockwise vortex, which confirms that this region is where the strain is accumulated and possesses medium-strong seismic risk.

| Baseline          | Trend | State   | Rate/mm·a⁻¹ | Error/mm |
|-------------------|-------|---------|-------------|----------|
| GSAX-GSJY         | NW    | Extension | 0.40        | 0.01     |
| GSDH-DLHA         | NW    | Extension | 1.71        | 0.01     |
| GSDH-GSJY         | NW    | Extension | 0.80        | 0.01     |
| GSDX-GSGL         | NW    | Extension | 2.41        | 0.01     |
| GSGT-GSML         | NW    | Extension | 0.49        | 0.01     |
| GSJT-GSGL         | NW    | Extension | 0.54        | 0.02     |
| GSJT-GSPL         | NW    | Extension | 1.83        | 0.02     |
| GSJY-GSGT         | NW    | Extension | 0.39        | 0.01     |
| GSMA-SCSP         | NW    | Extension | 4.08        | 0.02     |
| GSGL-GSML         | NW    | Extension | 1.60        | 0.01     |
| GSWD-GSMX         | NW    | Extension | 0.51        | 0.02     |
| NMAZ-NXYC         | NW    | Extension | 1.49        | 0.03     |
| QHGE-QHMD         | NW    | Extension | 8.43        | 0.02     |
| QHQL-GSGL         | NW    | Extension | 0.40        | 0.03     |
| NXZW-GSIN         | NW    | Extension | 2.98        | 0.01     |
| GSGL-NMAY         | NW    | Extension | 0.33        | 0.03     |
| SNMX-GSLX         | NW    | Extension | 2.23        | 0.03     |
| SNTB-GSIN         | NW    | Extension | 0.001       | 0.02     |
| QHGC-GSJY         | NW    | Extension | 0.13        | 0.02     |
| QHDL-GSMX         | NW    | Extension | 0.15        | 0.01     |
| GSGT-NMAY         | NW    | Extension | 0.73        | 0.02     |
| GSXD-GSJT         | NS    | Extension | 1.61        | 0.01     |
| GSWD-GSLX         | NS    | Extension | 1.03        | 0.02     |
| NMEJ-NMAY         | NS    | Extension | 0.24        | 0.01     |
| DLHA-GSJY         | NE    | Shorten   | -5.06       | 0.01     |
| DLHA-QHQL         | NEE   | Shorten   | -3.88       | 0.01     |
| GSML-QHQL         | NE    | Shorten   | -1.12       | 0.01     |
| GSMX-GSDX         | NNE   | Shorten   | -1.09       | 0.01     |
| GSWD-SNTB         | NE    | Shorten   | -0.69       | 0.02     |
| NMAZ-GSML         | NE    | Shorten   | -1.95       | 0.01     |
| NXYC-NXHY         | NNE   | Shorten   | -1.44       | 0.02     |
| SCSP-GSWD         | NE    | Shorten   | -3.29       | 0.02     |
| QHGE-DLHA         | NE    | Shorten   | -0.85       | 0.01     |
| YANC-GSPL         | NNE   | Shorten   | -0.07       | 0.02     |
| YANC-NXZW         | NEE   | Shorten   | -0.61       | 0.01     |
| YANC-GSIN         | NE    | Shorten   | -0.73       | 0.02     |
| GSGL-NMAZ         | NE    | Shorten   | -3.00       | 0.02     |
| GSWD-GSIN         | NE    | Shorten   | -0.54       | 0.02     |
| GSMA-GSJT         | NE    | Shorten   | -0.004      | 0.02     |
| QHGC-GSML         | NE    | Shorten   | -0.03       | 0.02     |
| QHMQ GSGL         | NE    | Shorten   | -0.003      | 0.02     |
| GSMA-GSMMX        | NEE   | Shorten   | -3.57       | 0.01     |
| QHGC-GSJYT        | EW    | Shorten   | -2.25       | 0.02     |
| QHGC-QHML         | NS    | Shorten   | -0.93       | 0.02     |
| NMWH-YANC         | NS    | Shorten   | -0.66       | 0.01     |
| QHGC-QHQL         | NS    | Shorten   | -0.06       | 0.02     |
| QHMD-QHMQ         | NW    | Shorten   | -2.84       | 0.01     |
| QHMQ-GSMQ         | NW    | Shorten   | -0.13       | 0.01     |

In summary, it is shown by the GPS baseline extension change rate result that the baselines in the
northeastern edge of Qinghai-Tibet Plateau demonstrate an overall characteristic of shortening in NE direction and extending in NW direction. A certain amount of strain energy might have been accumulated in the areas near the northern margin of Alkin Fault and the west boundary of Erdos Block. It can be judged based on the velocity field analysis result that the seismic risk in the west and east section of the intersecting area between Bayan Har Block and Qaidam Block is high; the west section of Northern Xiqinling Fault belongs to the inner ring of clockwise vortex and possesses medium-strong seismic risk.

4. Cognition and discussion

(1) The velocity field in the region ranging between 36°N and 42°N, between 94°E and 100°E, forms a counterclockwise vortex across different geological structural elements; The region surrounding by north to 34°N, east to 100°E, the north boundary of Qilian Block, Haiyuan Fault and Liupanshan Fault forms a clockwise vortex across different geological structural elements. The extrusion of Bayan Har Block in SE direction since 2009 has amplified obviously, which reflects that the Wenchuan Ms8.0 earthquake leads to the Longmenshan Fault unlocking in a wide range, causing the enhancement of correlated movement in SE direction in the NW side of Longmenshan Fault.

(2) The magnitude and direction of velocity vector on both sides of the west and east section of the intersecting area between Bayan Har Block and Qaidam Block differ, and the difference between the movement velocity magnitudes on both sides of the east section has enlarged in recent years. Besides, the directions of movement vectors on both sides of the northern boundary of Qilian Block differ greatly. In addition, the movement directions on both sides of the west section of Haiyuan Fault Zone are opposite. In recent periods, the movement velocity magnitude on both sides west to 105°N on Northern Xiqinling Fault differs greatly.

(3) The baselines in the northeastern edge of Qinghai-Tibet Plateau demonstrate an overall characteristic of shortening in NE direction and extending in NW direction. A certain amount of strain energy might have been accumulated in the areas near the northern margin of Alkin Fault and the west boundary of Erdos Block. The seismic risk in the west and east section of the intersecting area between Bayan Har Block and Qaidam Block is high; the west section of Northern Xiqinling Fault belongs to the inner ring of clockwise vortex and possesses medium-strong seismic risk.

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