

Horizontal movement and strain characteristics in Tianshan and its adjacent region with GPS deformation data^{*}

WANG Xiao-qiang¹⁾ (王晓强) LI Jie¹⁾ (李杰) Alexander Zubovich²⁾ WANG Qi³⁾ (王琪)

1) Earthquake Administration of Xinjiang Uygur Autonomous Region, Ürümqi 830011, China

2) Research Station of the Russian Academy of Sciences, Bishkek 720049, Kyrgyzstan

3) GPS Laboratory, Institute of Seismology, China Earthquake Administration, Wuhan 430071, China

Abstract

Based on the multiple-term horizontal velocity solutions of 230 GPS monitoring sites in Tianshan and its adjacent region, the GPS site velocity fields and crustal horizontal strain fields in the area have been obtained. The results show that the crustal shortening rate of Tianshan, with the longitude ($77^{\circ}\pm 1^{\circ}$)E as the boundary, gradually decreased towards two sides, from the south to the north, indicating that the pushing force of plate becomes weaker along with the fold deformation decreasing of the Tianshan. The direction of principal compressive strain of Tianshan and its adjacent area, nearly NNW, is basically perpendicular to the Tianshan cordillera trend, suggesting the distribution and variation of maximum principal compressive stress in Tianshan and its adjacent region resulted from collision and extrusion of Indian Plate. This paper indicates that the maximum shear strain field mainly concentrates on two areas, one is Isyk lake of North Tianshan, Kyrgyzstan, and the other is the juncture of Jiashi (South Tianshan) and Pamir arc faults. In the above areas, it can be shown from the epicentral distribution that the strong earthquakes mostly occurs at the high shearing strain accumulation filed or its edge.

Key word: GPS; Tianshan and its adjacent region; horizontal strain rate filed; maximum shear strain

CLC number: P315.72⁺7

Document code: A

Introduction

The Tianshan Mountain is the youngest cordillera in the present-day continental Asia, and its tectonic evolution is closely related to the collision and subduction between Indian Plate and Eurasian Plate in the Himalayas orogen since Cenozoic Era. The Tianshan Mountain is a typical Cenozoic rejuvenated mountain belt; it appears that the India Plate's thrusting and compressing northwards is probably the major driving force that caused the deformation of Tianshan. So, the two sides of the collision belt, North Tianshan and the area from Altay to Baikal, become extraordinarily stronger areas in the present-day crustal movement of Eurasian continent. Thus, it is of significance to study the horizontal deformation and strain for understanding geodynamics of other mountains in the interior of the Eurasian continent.

^{*} Received 2006-03-06; accepted in revised form 2006-10-09.

Foundation item: National Natural Science Foundation of China (40074024) and Natural Science Foundation of Xinjiang Uygur Autonomous Region (200321101).

Corresponding for author: cldwxqlj@263.net

There are two methods in general to analyze strain characteristics of crustal activities, the numerical value of strain field and the movement patterns of crustal deformation. One is to deduce the crustal activities and its characteristic strain field from the active fault and lithological characteristics (XIE *et al*, 1993; Molnar and Tapponnier, 1975, 1977), the other is from traditional geodesy (HU and LU, 1994). The above-mentioned methods are very helpful for us to research the characteristics of crustal strain, the local tectonics movement mechanism and the rule of tectonic movement (PENG, 1993; FU *et al*, 2000). However, what we get from the first method is an average accumulated results on a large-scale time, which is only taken as background analysis; on the other hand, the traditional geodesy have an large limitation in the observation scope and profundity of crustal movement. With the rapid development of GPS measurement in the field of geo-sciences, the crustal movement observation technology with high-accuracy, large-scale and high spatio-temporal resolution, not only enlarges our knowledge of tectonic deformation, but also plays an important role in assessing seismic risks and analyzing continental earthquake activities. In the paper, based on the GPS data from Tianshan GPS campaign and abroad we have calculated the horizontal velocity filed and established the displacement continuous function by the least squares procedure, then through partial derivative relationship between displacement and strain, we got the distribution of strain filed.

1 Computation model

To compute crustal strain rate filed from crustal deformation data, it is needed to firstly establish a linear function between deformation component and crustal strain tensor of the adjacent sites

$$\mathbf{U} = \mathbf{A}\mathbf{T} \quad (1)$$

where \mathbf{U} is the relative deformation component of the adjacent sites (displacement increment), \mathbf{T} is strain tensor, \mathbf{A} is transformation coefficient matrix.

Because we focus on horizontal displacement filed, so the GPS results, which are spatial vectors, are projected on the level, thereby the above function can be expressed as following (CHEN and TAO, 1987):

$$\begin{bmatrix} du_x \\ du_y \end{bmatrix} = \begin{bmatrix} \Delta x_{ij} & \Delta y_{ij} & 0 & \Delta y_{ij} \\ 0 & \Delta x_{ij} & \Delta y_{ij} & -\Delta x_{ij} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \\ \omega \end{bmatrix} \quad (2)$$

where du_x and du_y are displacement increment between the two sites in the deformation body; Δx_{ij} and Δy_{ij} are coordinates increment between the two sites; ε_x , ε_y , and ε_{xy} are the three components of horizontal strain rates, and ω is rotation component of the deformation body.

With many GPS sites data available, strain parameters can be obtained by the least squares method. In the process, weight is determined by the variance-covariance matrix of velocity and distance of the monitoring site away from the center point. If the above parameters are determined, maximum principle strain and maximum shear strain can be solved (CHEN and TAO, 1987).

2 Characteristics of velocity and strain rate fields

In this paper, one part GPS data come from East Tianshan (Xinjiang Uygur Autonomous Region, China), the other from West Tianshan (Kazakhstan and Kyrgyzstan). Raw GPS observation data (China) and pre-processed GPS data (h-files of Kazakhstan and Kyrgyzstan) are all analyzed

with GAMIT/GLOBK 10.06 data-processing software provided by MIT (Massachusetts Institute of Technology). Accordingly we computed and obtained the deformation velocities relative to Eurasian Plate and strain fields. The GPS data in this network have been collected in different ways. We got 7-term GPS data during 1998 to 2004 from Xinjiang GPS campaigns; and some data were offered by the Research Station of Russian Academy of Sciences in Bishkek by international cooperation, from 1998 to 2004. The two part data are measured by the same kind of the GPS receivers and with the same GPS work patterns.

In the present study, we deleted the mobile sites containing apparently abnormal motion and those less than 2-term data, so a total number of 230 sites were adopted. Among them, 126 sites in Xinjiang, 104 sites belong to Center Asia (Figure 1). Base on continuous distribution of GPS horizontal velocities field that is obtained by partial derivative, we have derived the maximum principle strain and maximum shear strain rate fields in Tianshan and its adjacent region.

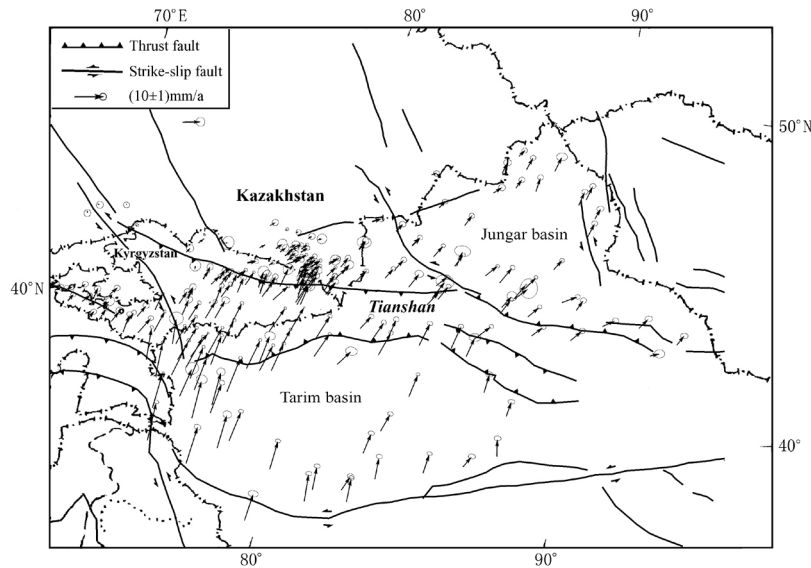


Figure 1 Velocity field of Tianshan and its adjacent region relative to Eurasian Plate during 1998 to 2004

Figure 1 shows the velocity solutions in the Tianshan and its adjacent region with the Eurasian Plate as referenced base. Influenced by the active collision between Indian and Eurasian Plates, Pamir Plateau, South Tianshan and Tarim block all gradually move northward with different velocity, suggesting that crustal shortening rate in the studied area gradually decreased towards two sides with the longitude ($77^{\circ}\pm 1^{\circ}$ E) as the boundary (WANG *et al.*, 2005). The deformation in the west part decreased distinctly faster than that in the east one. In China, the velocity in west Xinjiang area is larger than that in the east, and the north less than the south; whereas, in the west Tianshan region of Kyrgyzstan, the movement velocity in the east obtained by GPS is distinctly greater than that in the west. Because of the absent information of GPS data in the area to the south of 39° N and to the west of 75° E, we cannot get how the GPS velocity field motion in these regions is. But through analyzing the occurrence of strong earthquakes in the South Asia we can conclude that GPS velocities of the region (to the south of 39° N, to the west of 75° E) were gradually absorbed by the complex tectonic geological environment, so that the velocities become very smaller when reaching the Tajikistan and west of Kyrgyzstan.

There exists a distinct boundary of velocity field going through the location (36°N , 76°E) along the Pamir-West Kunlun arc fault. The GPS measurements indicate that the southern border moves southward at a rate about 20 mm/a; while at a rate of 10~15 mm/a from the border to 40.5°N . As a whole, the motion rate averagely decreased from 20 mm/a to 10~15 mm/a in the studied area. It can be seen from the profile along $75^{\circ}\sim 76^{\circ}\text{E}$ (Figure 2) that the rates of GPS sites decrease from (21 ± 1) mm/a to (1 ± 0.5) mm/a. For example, the S-N velocity component of the GPS site is 22 mm/a at the location (37°N , 75°E) nearby the Pamir arc fault, 14~15 mm/a on the South Tianshan thrust napped tectonics zone, and 11 mm/a close to the site (41°N , 75°E) in the intermontane basin of Tianshan. Then crossing the South Tianshan folding zone the velocity component gradually decreases to about 2.0 mm/a at position (43°N , 75°E). The crustal shortening rate is generally about 18~20 mm/a along the 75°E . The velocity field results obtained by the GPS measurement data in the present paper is basically consistent with that from geological model (Avouac and Tapponnier, 1993) and GPS (WANG *et al*, 2000), which indicates the shortening characteristic of the Tianshan along the above longitude.

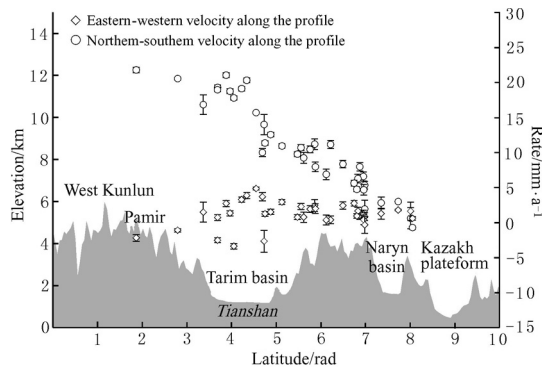


Figure 2 GPS velocity profile across Tianshan from south to north (35°N to 45°N)

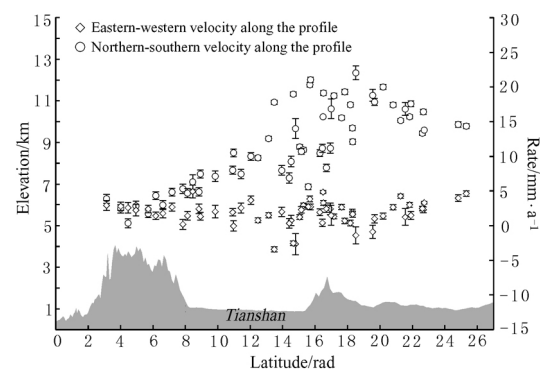


Figure 3 GPS velocity profile traversing the Tianshan from west to east (68°E to 95°E)

Central Tianshan moves gradually NNEward as a whole with an average velocity 9.4 mm/a, which is consistent with the direction of positive compression of Tarim block to Tianshan. The S-N component of GPS sites moves always with velocity (6.4 ± 0.9) mm/a at the location (44.2°N , 87°E) along the south edge of the Junggar block, indicating the crust is shortening at the east region of Tianshan. Figure 3 displays GPS sites motion profile covering the whole Tianshan Mountain from west to east. GPS sites velocities increased from 5 mm/a in the west of Tianshan (Central Asia) to the maximum 15~20 mm/a in central Tianshan ($83^{\circ}\text{E}\sim 88^{\circ}\text{E}$) and then gradually decreased. The motion reflects that deformation field has a clockwise rotation trending round some central point in the east region; furthermore it also shows its S-N direction deformation regularly decreases toward two sides along E-W direction when Central Tianshan is suffered from the northward compression of the Tarim block.

GPS velocity field results indicate the horizontal tectonic deformation of Tianshan area is characterized by that crust shortening decreases gradually towards two sides from south to north with the $(77^{\circ}\pm 1^{\circ})\text{E}$ as boundary, which reflects that the pushing force becomes weaker with Tianshan far away from edge of Eurasian Plate and the fold deformation of Tianshan accordingly turns slow from the west to the east (WANG *et al*, 2005).

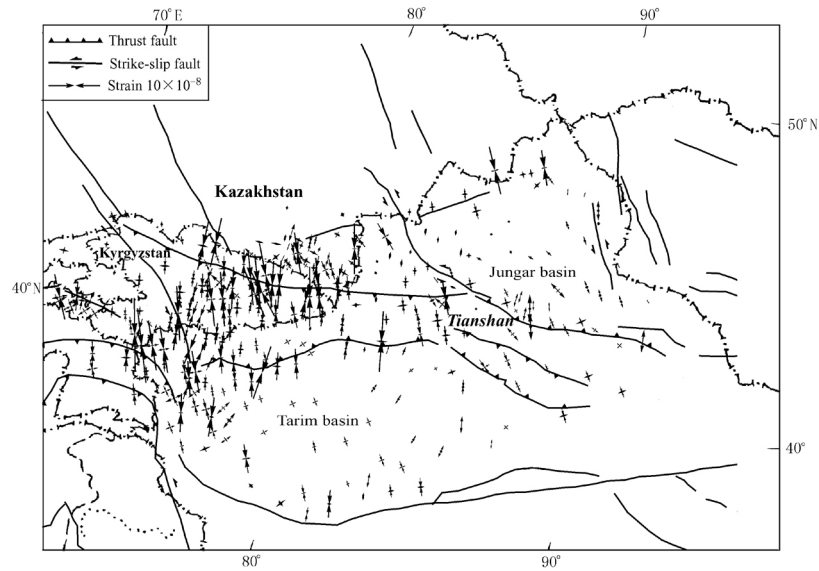


Figure 4 Distribution of principal compressive strain rate in Tianshan and its adjacent region

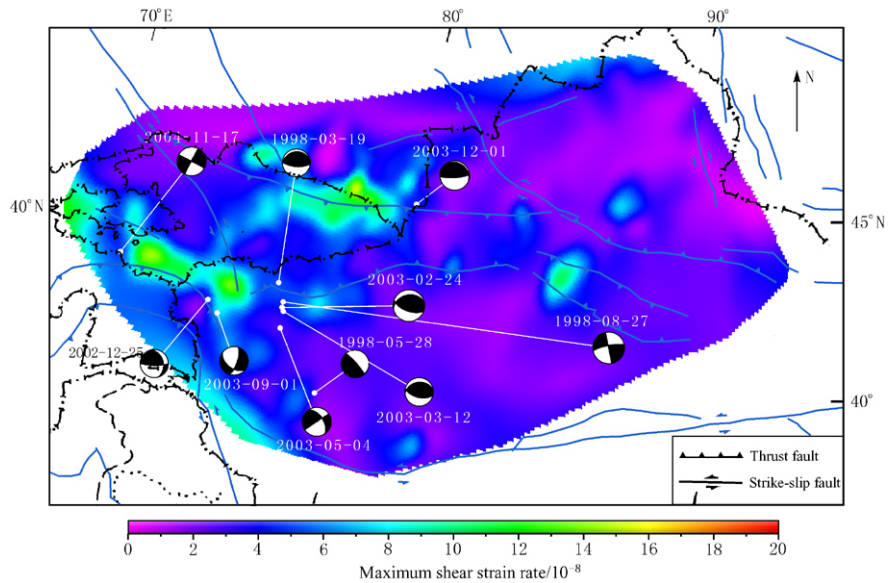


Figure 5 Contours of the maximum shear strain rate in Tianshan and its adjacent region

As a result of Cenozoic tectonic evolution, Tianshan becomes an area with strongest tectonic movement at present due to the collision between Indian and Eurasian Plates. How does the force act and what are the directions in two sides of Tianshan deserve our attention. The GPS solutions show that the area is dominated by principal compressive strain with the direction perpendicular to the Tianshan cordillera trend (Figure 4). Figure 4 shows the areas with large principal compressive strain rate concentrate relatively on the Tianshan folding zone. Especially, the juncture of the west to Isyk Lake of North Tianshan, in Kyrgyzstan, and South Tianshan and the Pamir arc faults is

characterized by compression and the historical strong earthquakes mainly occurred here. The principle compressive strain rates are dominantly distributed in the Tianshan earthquake belt in NNW trending. As far as the Tarim block and Junggar basin are concerned, the compressive strain rates are very small, although they are affected by the tensile stress in N-S and compression stress in E-W, which distinctly reflects that the major energy from quick pushing force of Indian Plate is absorbed after the multiple collisions among the Kunlun Mountain, Tianshan Mountain, and Tarim block.

Figure 5 shows the present-day maximum shear strain rate contours in Tianshan and its adjacent region. The great maximum shear strain rate concentrates relatively on the region composed of the Pamir arc fault, the north edge of West Kunlun fault, the South Tianshan nappe zone and the Tarim block, as well as the area between the Isyk lake and Ili basin, with the maximum value being $(24\pm 2)\times 10^{-8}/a$. Although the maximum shear strain rate contours cannot reflect the maximum shear strain direction, we can also deduce the shear strain in the studied area is in the direction of NNE from the relationship between maximum principle strain direction and maximum shear strain direction. On the other hand, by analyzing the distribution of focal mechanism solutions for historic strong earthquakes in Tianshan region, we can find that historic strong earthquakes almost occurred in the areas above-mentioned. The concentration of large shear strain rate indicates the complexity of geological tectonic movement and the possibility of earthquake occurrence in the future. For example, during the process of the Bachu-Jiashi $M_S=6.8$ earthquake (February of 2003), the quick cumulation of energy makes the crustal structure fracture to burst earthquake (JIANG *et al.*, 2003).

It has been discovered that the region, which includes the Pamir-West Kunlun fault and South Tianshan piedmont tectonic belt, cumulates large amount of strain energy due to quickly pushing northward from Indian Plate. Furthermore, the complex tectonic motion, distinct crustal shortening rate, and accumulating/releasing of high seismic energy, densely-distributed active faults and so on, are conditions for earthquake occurrence, so that the region becomes dangerous one of strong earthquake at present. JIANG *et al.* (2003) gave that most of the $M_S=6.0$ earthquakes occurred in the high-gradient zone of shearing strain rate and its edge. For example, for the $M_S=7.6$ Jiji earthquake of Taiwan on September 21, 1999, GPS measurement results had proved the earthquake occurred in the edge of the high-gradient zone of horizontal shearing strain rate.

3 Discussion and conclusions

In the paper, we have firstly derived the integral solution of horizontal strain characteristics and its spatial distribution on the basis of the GPS data of Tianshan region in Chinese mainland and the data of Central Asia. Undoubtedly, it is able to broaden our outlook for the neotectonics of Tianshan, enlarge the utilization of the GPS data in Xinjiang region to Central Asia, eliminate the localization of seismogenesis study on two sides of Tianshan, and expand our fields of vision to the whole Tianshan and Central Asia.

The present study suggests that the crustal shortening rate of Tianshan gradually decreased towards its two sides with the longitude ($77^\circ\pm 1^\circ$)E (38° N to 42° N) as the boundary from south to north. From the shear strain rate contours, we can clearly see that there certainly exists the probability of earthquake occurrence in the high-gradient zone of shear strain rate and its margin. Limited by the distribution and number of existing GPS sites in Xinjiang region, it is not enough to fully monitor active tectonic movement in Tianshan region. So, it is hoped that with the increasing

tempo-spatial density of GPS sites, by using appropriate geophysics and geodesy data, further study on crustal movement and tectonic deformation will be carried out, and it is of great significance to protection against and mitigating earthquake disaster in the future.

Acknowledgments We are grateful to Professor WU Yun of Institute of Seismology, China Earthquake Administration, for useful suggestion.

References

- Avouac J P and Tapponnier P. 1993. Kinematic model of active deformation in central Asia [J]. *Geophysics Res Lett*, **20**: 895-898.
- CHEN jian and TAO Ben-zao. 1987. *Geodetic Deformation* [M]. Beijing: Seismological Press: 447-464 (in Chinese).
- FU Rong-Shan, XU Yao-min, HUANG Jian-hua, *et al.* 2000. Numerical simulation of the compression uplift of the Qinghai-Xizang Plateau [J]. *Chinese J Geophys*, **43(3)**: 346-359 (in Chinese).
- HU Ming-cheng and LU Fu. 1994. *Recent Geodesy* [M]. Beijing: Surveying and Mapping Press: 76-787 (in Chinese).
- JIANG Zai-sen, MA Zong-jin, NIU An-fu, *et al.* 2003. Approaches and preliminary results of crust movement researches based on the GPS in China [J]. *Earth Science Frontiers*, **10(1)**: 71-79 (in Chinese).
- Molnar P and Tapponnier P. 1975. Cenozoic tectonics of Asia: Effects of a continental collision [J]. *Science*, **189**: 410-426.
- Molnar P and Tapponnier P. 1977. Relation of the tectonics of eastern China to the Indian-Eurasia collision: Application of slip line field theory to large-scale continental tectonic [J]. *Geology*, **5**: 212-216.
- PENG Shu-sen. 1993. On the Neotectonic movement reflected by the geodesic deformation measurement in Tianshan [J]. *Inland Earthquake*, **7(2)**: 136-141 (in Chinese).
- WANG Qi, DING Guo-yu, QIAO Xue-jun, *et al.* 2000. Research on present crustal deformation in the southern Tianshan (Jiashi), China by GPS geodesy [J]. *Acta Seismologica Sinica*, **13(3)**: 280-287.
- WANG Xiao-qiang, LI jie, WANG Qi, *et al.* 2005. Analysis of present-day crustal deformation of Tianshan [J]. *Journal of Geodesy and Geodynamics*, **25(3)**: 63-68 (in Chinese).
- XIE Fu-ren and ZHU Jing-zhong, LIANG Hai-qing, *et al.* 1993. Basic characteristics of recent tectonic stress field in southwest China [J]. *Acta Seismologica Sinica*, **6(4)**: 843-855.