

Contemporary Deformation of the Fenwei faulted zone From Global Positioning System Data

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Key Points:

- Fenwei faulted zone is a region with high-level of earthquake hazard
- Fenwei faulted zone is undergoing significant tectonic extension and right-lateral strike-slip
- Relative motion between blocks contributes to the formation of the Fenwei faulted zone and repeated large earthquakes with short intervals

Abstract

The Fenwei faulted zone is a region with high level of seismic hazard. Different models are proposed for the formation of the Fenwei faulted zone, but none has given its specific kinematic mechanism. Using updated GPS data covering the eastern China, we discover that although the Ordos block, the North China Plain and the South China block are moving in the southeast direction, the relative motion between them is obviously different: there is basically no shear slips inside the Weihe graben, and the extension rate across it is significant; in addition, the Shanxi graben system has roughly equal extensional and right-lateral strike-slip components. We suggest that rapid southeastward motion of the rigid South China block and the North China Plain, with respect to the Ordos block, has imposed intensive tectonic extension on the Fenwei faulted zone forming the contemporary deformation.

1. Introduction

The Fenwei faulted zone (FFZ, including the Weihe graben and the Shanxi graben system) has been the political and cultural center in western China with a dense population and prosperous economy. However, the FFZ is also famous for its high level of earthquake hazards. There have been 8 earthquakes of magnitude greater than 6 and 2 earthquakes of magnitude greater than 7 so far (Figure 1).

The Fenwei faulted zone, located at the position of intersection and superposition between three major blocks (the Ordos block, the North China Plain (NCP) and the South China block), has been an intensively active basin in the Cenozoic. The Fenwei faulted zone whose trend is NEE to NNE from S to N is characterized by transtensional right-lateral shear faults to the east, and is bounded by left-lateral shear extensional faults to the south. Over the past three decades, different models have been developed to describe the tectonic evolution of the graben systems around the Ordos block (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977; Tian et al., 1992; Northrup et al., 1995; Yin, 2010; Liu et al., 2007). Some researchers considered that the tectonic deformation and evolution of the Ordos area are the result of the far-field Indo-Asian collision (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977). Alternatively, Some interpreted the idea that North China crustal thinning and volcanic activity may be closely related to the westward subduction of the Pacific plate beneath the Eurasian continent and the roll-back mechanism (Tian et al., 1992; Northrup et al., 1995).

Previous GPS observations from 1992 to 2002 show almost no deformation across the FFZ, neither extension nor strike slip (He et al., 2003; Shen et al., 2000; Wang et al., 2001). Zhang et al. (2018) used updated GPS data to conclude that there is no obvious east-west extension across either the Shanxi graben and the entire NCP. It is unlikely that a region with such frequent great historical earthquakes associated with no present-day deformation. There must be crustal deformation that has not yet been observed. Contradict the previous GPS studies, Modern seismicity indicates active rifting (Figure 1). Wesnousky et al. (1984) estimated a coseismic extension rate around ~1.0 mm/yr based on seismic moment data. This is close to the 0.5–1.6 mm/yr extension rate averaged over the Late Pliocene-Quaternary time (Zhang et al., 1998). Surface ruptures associated with great historical earthquakes on the graben-bounded faults do show prominent normal faulting with right-lateral strike-slip component such as the 1556 Huaxian earthquake (Rao et al., 2014), the 1303 Hongdong earthquake (Xu et al., 2014, 2019; Jiang et al., 2004). Fault plane solutions of recent earthquakes also show overwhelming dip-slip and strike-slip motions on almost vertical dipping NNE-trending faults planes such as the 1991 Datong earthquake (Figure 1; He et al., 2003; Xu et al., 2012, 2019; Chen & Nabelek, 1988; Gao et al., 2016). Hao et al. (2016) used precise leveling data observed in the period of 1970–2014 around the Ordos block to conclude that with respect to the stable Ordos, the Weihe and southern Shanxi grabens are subsiding at the rates of 4–6 mm/a. The subsidence of the Shanxi graben indicates that the graben is experiencing extensional movement on a long timescale.

Recently, Zheng et al. (2017) have published GPS velocity field that covers entire China and vicinity regions. In this paper we use a subset of their GPS data in the entire eastern China that spans three crustal blocks rather than restricting our analysis to only one block or one fault, trying to understand the pattern of contemporary tectonic deformation of the FFZ and earthquake hazards in the graben systems. The velocity field of tectonic deformation provides an important basis to understand the dynamic driving mechanism and is one of the keys to address the issues of Cenozoic deformation in eastern China.

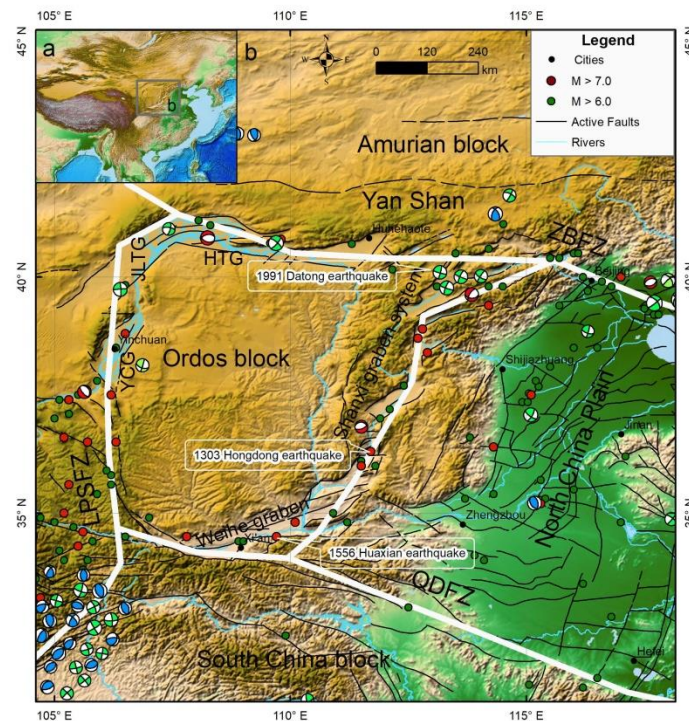


Figure 1. Seismotectonic map of the North China. (a) The thick gray lines outline boundaries of Figure 1b. (b) The bold white lines are block boundaries. Earthquake focal mechanism (>4.0) is taken from <http://www.ceic.ac.cn/>. HTG: Hetao graben; ZBFZ: Zhangjiakou-Bohai fault zone; QDFZ: Qinling-Dabie fault zone; LPSFZ: Liupanshan fault zone; YCG: Yinchuan graben; JLTG: Jilantai graben.

2. Geological setting

The Ordos block is characterized by low strain rate and seismicity. In contrast, the margins of this stable block have been active since Cenozoic. The block is surrounded by four graben systems: the Yinchuan graben along its western margin, the Hetao graben along its northern margin, the Shanxi graben system along its eastern margin, and the Weihe graben along its southern margin (Yin et al., 2010; Zhao et al., 2017, Figure 1).

During the Yanshan movement, the Ordos block showed intermittent uplift and subsidence movements, while strong tectonic activities occurred on its periphery. In the Hetao and Weihe basins, a near east-west trend compressional tectonic belt is formed, while a NE-NNE trend compressional tectonic belt is formed in the Shanxi and Yinchuan basins. The basic tectonic setting formed by the Mesozoic, especially the Yanshan movement, laid the foundation for the geological evolution in this area in the Cenozoic. During the Cenozoic era, the most outstanding features of the southwestern margin and adjacent areas of Ordos were the formation of a series of extensional faulted basins on its periphery and the formation of thrusting fault zone on its southwestern margin. According to the sediment distribution of the Ordos block and the developmental characteristics of the faulted zones, the tectonic activities of the area can be roughly divided into three main stages: (1) the Weihe basin, the Yinchuan basin and the Jilantai basin begin to develop in the Eocene. It had basically formed at the end of the Oligocene. (2) at the end of the Miocene, the Ordos Block continued to uplift. and the peripheral faulted zones continued to develop. In addition, the Weihe faulted zone extended eastward into Shanxi, forming the Yuncheng basin; (3) at the end of the Pliocene, controlled by the NE-NNE trend faults, the Shanxi faulted zone was basically formed. (Deng et al., 1999; Zheng et al., 2006; Wang et al., 2010; Wang et al., 2013; Chen et al., 2013; Shi et al., 2013; Chen et al., 2015; Zhao et al., 2017; Working Group of the Active Fault Zone Around the Ordos, Chinese Seismological Bureau, 1988).

The northern boundary of the Ordos block and NCP consists of the EW-trending Hetao graben and the Zhangjiakou-Bohai fault zone (Figure 1), separating the North China block from Yan Shan mountains or the Amurian block (Zhang et al., 2018; Figure 1). The southern boundary of the Ordos block and NCP is the approximately EW-trending Qinling-Dabie Shan range-front fault zone (Figure 1). Geomorphological and seismological studies suggest that this fault zone has limited Quaternary tectonic activity (Deng et al., 2003; Zhang, Deng, et al., 2003).

The western boundary of the NCP is the Shanxi graben system where great historical earthquakes occurred mostly inside the sedimentary basin, suggesting intensive tectonic activity on this boundary. The western boundary of the Ordos block is the NS-trending Jilantai-Yinchuan graben and the Liupanshan thrust-fold zone, which both have intensive tectonic activity and seismicity.

3. Pattern and Rate of Deformation From GPS Analyses

3.1. GPS Data and Relative Motion Among the Crust Blocks in Eastern China

The principal data used for this study come from the Crustal Movement Observation Network of China collected during 1998 to 2015. The procedures of data collection and process are described recently in detail by Zheng et al. (2017).

Figure 2 depicts motions of different crustal blocks relative to the fixed Eurasia. Stations in the Ordos block, move with respect to the fixed Eurasia at velocities of 4 to 7 mm/yr in the directions ranging from N100° to 130°E (Figure 2), suggesting almost a stable relative motion between the Ordos block and Eurasian plate.

Most of the GPS velocity vectors in the NCP are within the rates of 5.0 ± 1.5 mm/yr and the directions of N100°–120°E (Figure 2) despite of isolated large local variations. It is worth to note that the velocities gradually increase from 1–2 mm/yr in the Amurian block to 5–6 mm/yr in the interior of NCP (Figure 2, Zhang et al., 2018).

The South China block is regarded as a tectonically stable block due to the absence of active faults and strong earthquakes (Deng et al., 2003; Zhang, Deng, et al., 2003). GPS velocities show coherent movement of the South China with a rate of 7–8 mm/yr in the directions of N100°–120°E (Figure 2, Zhang et al., 2018). No velocity gradient can be identified in the rigid South China block. Similar to the northern edge of NCP, the average 5–6 mm/yr relative motions near the southern edge of NCP gradually change to average 7–8 mm/yr velocities in the South China block (Figure 2, Zhang et al., 2018).

3.2 Velocity Profiles in the Direction of N0°E

The N0°E velocity profiles is constructed to explore the movement differences between the South China block and the Ordos block (the gray polygon in Figure 2). It can be seen from N90°E velocity components in the direction of N0°E velocity profiles that there is a obvious left-lateral strike-slip rate difference of 2.27 ± 0.52 mm/yr between the South China block and the Ordos block within a distance of about 200km across the Weihe graben (Fig 3a). Figure 3b shows that both the South China block and the Ordos block move southward at the rate of -2.78 ± 0.98 mm/yr and -2.27 ± 0.80 mm/yr, respectively. The 0.51 ± 0.18 mm/yr rate difference demonstrates that the extension rate of the Weihe graben in the NS direction is relatively small, but can be detected easily.

Wang et al. (2011) reported the predicted fault slip rates of the Weihe rift that the Weihe rift has a left-lateral strike-slip rate of 1.4 ± 0.5 mm/yr and extension rate of 0.5 ± 0.3 mm/yr. These results are comparable with our estimates.

3.3 Velocity Profiles in the Direction of N160°E

We have constructed velocity profiles across the South China block and the Ordos block in the direction of N160°E to study if there are differential motions perpendicular to the main structure trend in the Weihe graben (the yellow polygon in Figure 2; Figure 3c and 3d).

From N70°E velocity components basically parallel to the main structural lines of the Weihe graben in the N160°E velocity profiles (Figure 3c), we can find that there is no obvious differences in shear slip rates across the Weihe graben indicating that the formation of the Weihe graben may not be related to the strike-slip movements of the internal faults in the graben or the contemporary deformation of the Weihe graben is not dominated by strike-slip movements.

In Figure 3d, although both the Ordos block and the South China block move southeastwards, however, there are obvious rate differences on both sides of the Weihe graben or across the Huashan Fault. From the beginning to a distance of ~ 400km, the rates remain within a stable range of ~ 4.0 mm/yr. But the rates show an rapid growth while entering the South China block. The rates maintains averaged ~ 5 mm/yr in the interior of the South China block (Figure 3d). The rate difference of about ~ 1 mm/yr between the South China block and the Ordos block in the N160°E direction, which is twice as much the extension rate in the direction of N0°E velocity profiles means that the main extensional direction of the Weihe graben is NW-SE trend. The seismogenic fault of the catastrophic 1556 Huaxian earthquake killing 800 thousands people is thought to be the roughly NE-NEE trend Huashan fault. The fault is a Holocene active fault, controlling the Quaternary subsidence center of the Weihe basin and the highest terrain. Interestingly, the ~ 1mm/yr we observed is basically equivalent to the ~ 1mm/yr dip-slip rate of the Huashan fault from geologic studies (Xu et al., 2017; Yang et al., 2012; Li et al., 2015; Li et al., 1983; Rao et al., 2014) indicating the Huashan fault absorbs the main extension deformation.

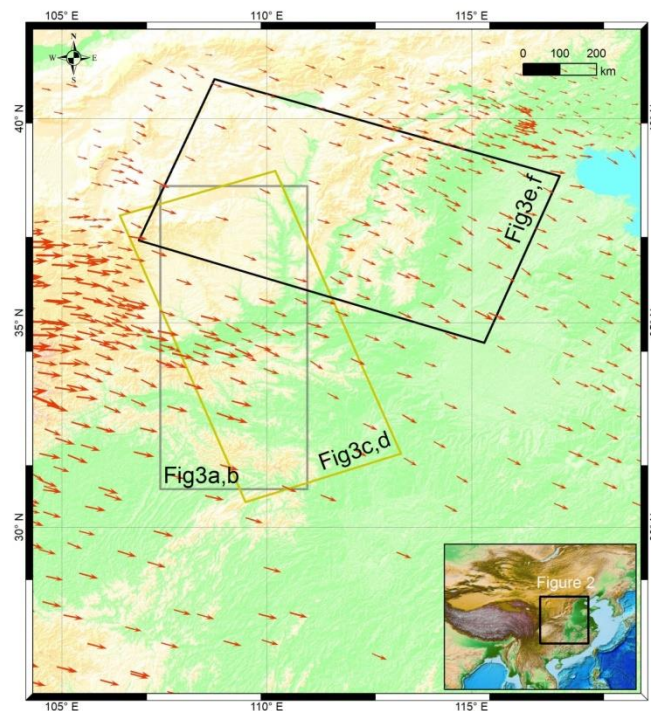


Figure 2. Global Positioning System (GPS) velocity field of the North China in the Eurasia fixed reference frame. The gray polygon marks data used to plot Figures 3a and 3b. The yellow polygon covers velocity vectors plotted in Figures 3c and 3d. The black polygon covers velocity vectors plotted in Figures 3e and 3f. The insert shows the location of the figure. The GPS data are from Zheng et al. (2017).

3.4 Velocity Profiles in the Direction of N110°E

To probe deformation of the Shanxi graben system we construct velocity profiles in the direction of N20°E and plot velocity components of both N20°E and N110°E for stations in the Ordos block, the NCP (the black polygon in Figure 2; Figures 3e and 3f).

The N20°E components of GPS stations plotted on the profile are intended to detect if there is strike-slip movements between the Ordos block and the NCP in roughly NS orientation (Figure 3e). The profile obviously depicts that both the Ordos block and NCP move slightly southward (Figure 3e). However, the profile across the Shanxi graben system and NCP shows different kinematic patterns from the Ordos block (Figure 3e). Two interpretations can be proposed. One is that rate differences across the Shanxi graben system behaves as step-wise variety showing by the cyan rectangle in Figure 3e to result in about 0.8 mm/yr right-lateral strike-slip. The other one, shown by the gray polygon, is that the rates increases progressively southeastward to create right-lateral strike-slip within a broader range, whereas the Ordos block maintains its velocities within a stable range (Figure 3e).

The N110°E components of GPS stations plotted on the profile are intended to detect if there is extension or contraction between the Ordos block and NCP in roughly EW orientation (Figure 3f). The profile obviously depicts that both the Ordos block and NCP move eastward (Figure 3f). However, the profile across the Shanxi graben system and NCP also shows different kinematic patterns from the Ordos block (Figure 3f). Two interpretations can be proposed. One is that rate differences across the Shanxi graben system behaves as step-wise variety showing by the cyan rectangle in Figure 3f to result in about 0.7 mm/yr extension rate. The other one, shown by the gray polygon, is that the rates increases progressively southeastward within the NCP, whereas the Ordos block maintains its velocities within a stable range (Figure 3f).

Wang et al. (2011) reported the predicted fault slip rates of the Shanxi rift that the Shanxi rift has a right-lateral strike-slip rate of 0.6 ± 0.5 mm/yr and extension rate of 0.8 ± 0.3 mm/yr. These results are basically consistent with our estimates.

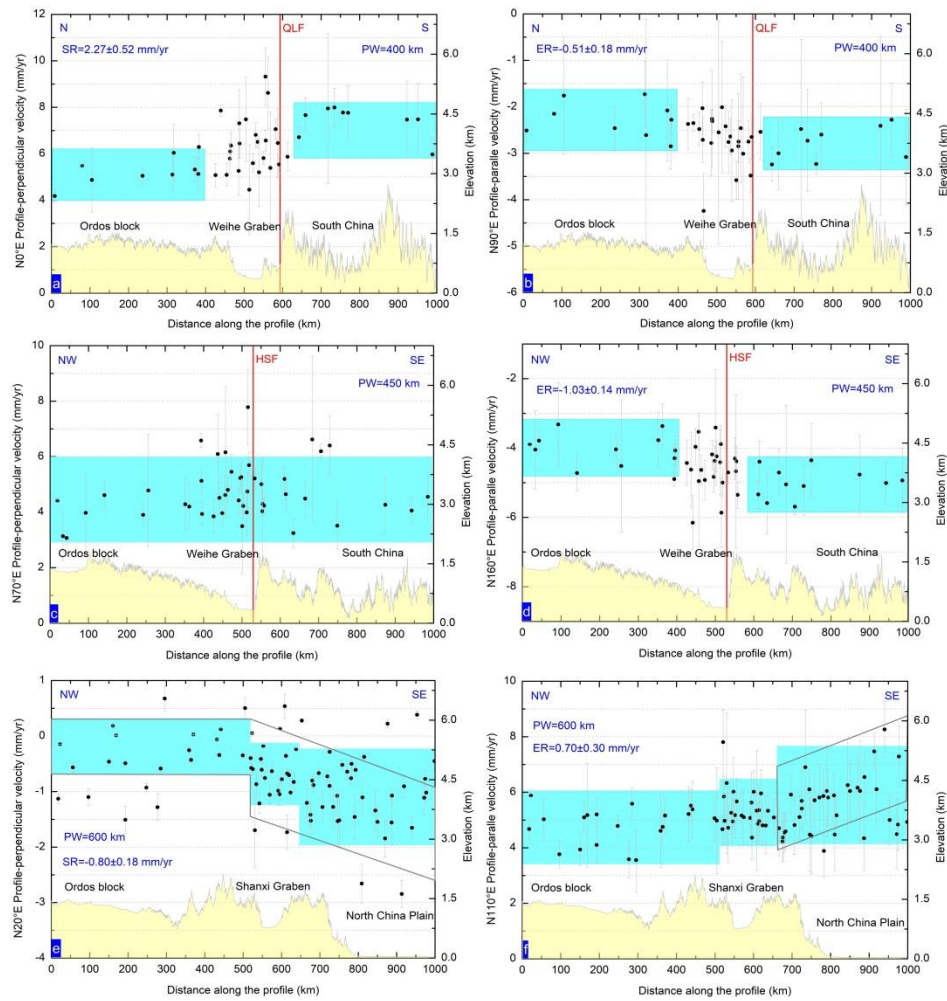


Figure 3. Global Positioning System (GPS) velocity profiles and swath profiles. GPS velocity components are designated that eastward and northward are positive. The cyan strips mark acceptable ranges of average velocity components. SR: strike-slip rate; ER: extension rate. PW: profile width. QLF: Qinling fault; HSF: Huashan fault. The locations of each profile are referred in Fig 2.

4. Model of Deformation and seismicity

The pattern of deformation of the FFZ is very different from the NCP (Zhang et al., 2018) where the roughly EW-trending left-lateral shear zone has been accommodated by a group of nearly NS-trending right-lateral faults and from the eastern Tibet (England & Molnar, 1990) where the NS-trending right-lateral shear zone bounds a group of EW-trending left-lateral faults within the zone (e.g., Zhang et al., 2018; England & Molnar, 1990; Nur et al., 1989; Savage et al., 2004).

Figure 4a shows original cartoon that the Ordos block and NCP behaves as a whole block and the South China block is rigid.

During the period of relative motion between different blocks, the South China block moves ESE-ward more rapidly than the Ordos block to create a left-lateral simple shear on the southern border of the Weihe graben and a extension to the Weihe graben in the both NS and SES direction (Figure 3, Figure 4b). The left-lateral simple shear provides space for the further expansion of the Weihe graben (Figure 4b). As the extension continuing, the pure shear might have taken advantage of weak zones forming a series of NEE-trending normal faults in the Weihe graben. The NEE-trending faults absorb most interseismic shearing to accumulate elastic strain. When strain accumulation exceeds the frictional strength of a particular NEE-trending fault, great earthquake occurs to release the accumulated strain. The earthquake rupture and permanent deformation are expected to be pure dip-slip on the NEE-trending faults (Figure 4b).

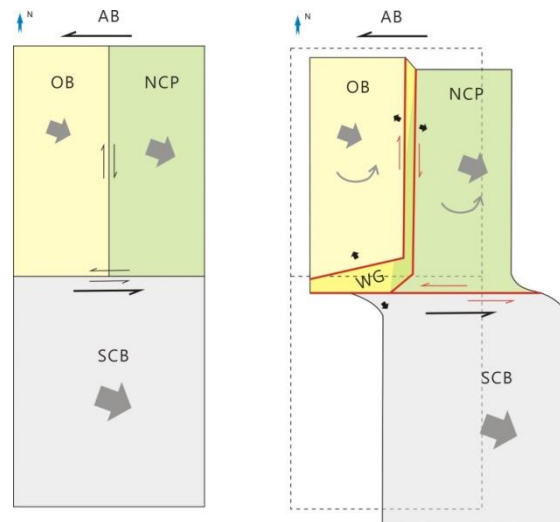


Figure 4. Conceptual cartoon diagram showing deformation pattern of the Weihe-Shanxi graben . (a) Original cartoon before deformation. (b) Pattern of permanent deformation in the long term induced by relative motion among the Weihe graben, the NCP and the South China block. The red lines shows active faults. The gray bold arrow denote direction and rate of the block motion. The small black bold arrow denote direction of the tectonic extension. AB: Amurian block; OB: Ordos block; NCP: North China Plain; SCB: South China block. WG: Weihe graben.

The NCP moves ESE-ward more rapidly than the Ordos block to create a right-lateral simple shear on the eastern border of the Ordos block and a extension to the Shanxi graben system in the ~ EW direction forming the Shanxi graben system (Figure 4b). The right-lateral strike-slip and extension rates are about 0.8 mm/yr and 0.7 mm/yr respectively. This pattern of transextensional deformation contributes to the formation of a series of small pull-apart basins such as Linfen basin, Taiyuan basin and Datong basin from south to north. Geological and seismological observations support the scenario of this kind of deformation. Almost all great historical earthquakes in the Shanxi graben system occurred along the NNE-trending faults with both dip-slip displacements or strike-slip displacements. The surface ruptures of the 1303 Hongdong earthquake, for example, dominated by dip-slip displacements with some horizontal displacements from geological observations and paleoearthquake trenches (Xu et al., 2014, 2019; Jiang et al., 2004). The Hongdong M8.0 earthquake in 1303 was the earliest magnitude 8 earthquake in China based on historical documents and the largest earthquake recorded in the Shanxi graben system. Fault plane solutions of large historical earthquakes (Figure 1) also manifest prominent right-lateral strike-slip displacements in the northern segment and dip-slip displacements in the southern segment (He et al., 2003).

This pattern of deformation of the FFZ causes repeated occurrences of large earthquakes with relatively short interseismic intervals (Xu et al., 2014, 2019). The characteristics of the FFZ could be summarized as follows: First, the strain produced by extension-induced pure shear can be easily concentrated on the main boundary faults. Second, due to continuing extension in the long run, the strain rate across each fault can be sustained to account for big earthquakes. Third, the secondary faults will be produced by earthquakes and accommodate the interseismic strain, which in turn could generate earthquakes.

5. Discussion and Implication

To summarize, the most important discovery of our new analysis of GPS data is that the contemporary deformation of the FFZ is dominated by almost pure normal slip which is driven by the relative motion between the Ordos block, NCP and the South China block (Figure 4). The extension is accommodated by right-lateral strike-slips along the NNE-trending faults in the Shanxi graben system and left-lateral strike-slips between the Ordos block and the South China block. This pattern of deformation provides important implications for earthquake occurrences and geodynamics for the FFZ.

Seismic hazards and risks in the eastern section of the Weihe graben are much higher than its western section. An important reason for this is that extension rates in the SES direction across the eastern section are ~2 times bigger than the rates in the NS direction across the western section. While seismic hazards and risks in the Shanxi graben system are also high. The reason for this is that the strike-slip and extension rates in the Shanxi graben system are basically equivalent to each other. It is likely that future large earthquakes will continue to occur in the whole Shanxi graben system on the NNE-trending faults with both dip-slips and right-lateral strike-slips.

The formation of the FFZ, as a Cenozoic extensional basin, was due to crustal extension and lithospheric thinning associated with geological processes of “block motion”. Our results indicate that the processes that driving the extension are continuing in a long time scale. The geodynamic processes that caused the processes are unclear, but based on the maximum extension direction of the Weihe graben, we propose a combined model that rapid eastward motion of the eastern China, driven by eastward growth of the Tibetan Plateau, has created the eastward motion of the NCP and the South China block relative to the stable Ordos block, accompanied by the westward subduction of the Pacific plate, accelerating the tectonic extension of the FFZ.

Acknowledgments

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