Crustal deformation and strain fields of the Weihe Basin and surrounding area of central China based on GPS observations and kinematic models

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\textbf{ABSTRACT}

The Weihe Basin in central China is characterized by its complex geological background and intense tectonic activity. This study examined the characteristics of the crustal deformation and strain field of the Weihe Basin and its surroundings based on campaign Global Positioning System (GPS) data acquired during 2001–2011. We first analyzed the variations of crustal movement and we calculated the crustal strain rates by establishing sound strain models. Both the characteristics of the strain field and the correlation between the maximum shear strain field and the distribution of seismicity were investigated. Our results indicated that the overall crustal movement of the Weihe Basin region was temporally continuous during 2001–2011, despite short-term fluctuation during 2007–2008. We found that western and eastern parts of the Weihe Basin region presented considerably different tectonic characteristics with predominantly compressional strain in the west and extensional strain in the east. However, the magnitude and direction of the overall crustal movement, and the relative differential motions of the Weihe Basin region, changed obviously during 2007–2008 with substantially increased compressional strain in western areas. We conclude that regions with higher shear strain are also those with frequent earthquakes, the distribution of which might have been affected by the M8.0 Wenchuan earthquake in May 2008. According to variations of the crustal deformation and the strain field, we further infer that western parts of the Weihe Basin region during 2007–2008 might have been affected by a northeastward extrusion caused by the Wenchuan earthquake. However, this dynamic effect might have gradually permeated to eastern parts of the Weihe Basin region during 2008–2011. The results obtained in this paper not only portray the current tectonic activity deformations but also the recent geodynamic processes of the Weihe Basin and its surrounding area.

\textbf{1. Introduction}

The Weihe Basin, located in Shaanxi Province in central China (Fig. 1a), is surrounded by the Qinghai–Tibet Block, Ordos Block, North China Block, and South China Block (Fig. 1b) (Feng et al., 2003; Dai et al., 2004; Shi et al., 2008; Qu et al., 2009, 2011; Yang et al., 2013; Rao et al., 2014; Lin et al., 2015; Gao et al., 2015; Jiang et al., 2016). The Weihe Basin and surrounding area (hereafter, referred to as the Weihe Basin region) is characterized by intense crustal activity, and it comprises an important component of the well-known Fen–Wei Seismic Belt (Fig. 1c) (Jiang et al., 2000; Myers and Gomez, 2010; Liu et al., 2016). Therefore, the Weihe Basin region, which constitutes an important natural laboratory for the study of active tectonic deformation in a typical intracontinental graben system, has attracted considerable attention from many researchers in the field of geoscience.

Recent geophysical, geological, and geodetic studies have revealed various important aspects of the Weihe Basin region. Its crustal structure has been studied based on geological investigations (Wang et al., 2014), and its orogenic tectonic movement has been investigated through the analysis of rock samples (Chen et al., 2015). The tectonic activities and structural features of the active faults of the Weihe Basin region have been revealed by fault profiles (Shi et al., 2008), high-resolution remote sensing imagery (Rao et al., 2014), and field observations (Feng et al., 2003; Deng, 2007; Li et al., 2015; Lin et al., 2015). The earthquakes that have occurred within the basin have been studied using earthquake catalogs (Liu et al., 2016) and field investigations (Rao et al., 2014). Furthermore, the deep crustal structure and geophysical characteristics beneath the basin have been determined using seismic wave velocity (Bai et al., 2008) and seismic tomography (Pan and Niu, 2011; Ren et al., 2013; Guo and Chen, 2016). The features and mechanisms of ground fissures have been studied by interferometric synthetic aperture radar (Qu et al., 2014a), field investigations, and
mechanical simulations (Peng et al., 2013). The tectonic stress field and structural extension of the Weihe Basin region have been modeled using numerical simulations (Zhang et al., 2011), kinematic analysis of faults (Mercier et al., 2013), field observations and thermochronology (Liu et al., 2013). Moreover, the crustal deformations and tectonic movements have been analyzed based on Global Positioning System (GPS) observations (Dai et al., 2004; Qu et al., 2011; Zhang et al., 2012; Cui et al., 2016).

Previous studies that have applied different methods to investigate the crustal deformations and tectonic characteristics of the Weihe Basin region constitute important references for the regional geodynamics.

Among the abovementioned methods, GPS technology has been proven especially useful for studying crustal deformation and geodynamic processes. Although GPS data have been used to describe the general characteristics of the crustal motion of the entire Weihe Basin region, there has been a lack of detailed study on the variations of relative motions and strain fields within the basin. Variations of both the GPS velocities and the crustal strain fields are useful not only for describing the development of tectonic activity, but also for characterizing the internal mechanisms of ongoing basin deformation. Moreover, variations of relative differential velocities can reflect more clearly the interior motions of the basin.

Fig. 1. Location of the Weihe basin and its surroundings in China, as well as the major plate boundaries in and near mainland China (Fig. 1a). The red dashed box indicates the Weihe basin and its adjacent tectonic belts. The black thin dotted lines indicate the division of the tectonic units and their boundaries, such as the Qinghai-Tibet Block, the Ordos Block, the North China Block and the South China Block. The blue closed outline represents the whole Shaanxi province. The black rectangular box is the specific location of the study area: the Weihe basin and its surrounding area (Fig. 1b). The red thick dotted lines indicate the scope of the Weihe basin determined by geological data (Peng, 1992b, Fig. 1b). The white solid lines represent the major active faults (Zhang et al., 2005). The small double circles represent the major cities. The light blue curves represent the rivers. The solid filled circles (black and/or red) of varying size indicate the epicenters and magnitude of the large historical earthquakes within the Weihe basin region (Lin et al., 2015). Fig. 1c shows the stratigraphy of the Weihe basin obtained from the wide-angle reflection method (Ren et al., 2012). Fig. 1d shows the distribution of major faults within the Weihe basin. F1–F10 represent the numbers and names of these major faults (Zhang et al., 2012). The red solid lines represent ground fissures within the Weihe basin (Zhang et al., 2012) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
This study used GPS data from the Weihe Basin region, which were acquired during different periods by the Seismological Bureau of Shaanxi Province and the Crustal Movement Observation Network of China. The objectives were to investigate the variations of crustal velocity fields and relative differential motions within the basin, and to explore the variations of crustal strain fields through establishing sound strain models. Finally, the variations of the strain fields, as well as the correlation between the maximum shear strain field and seismicity, were examined.

2. General tectonic background

The Weihe Basin is a Cenozoic rift basin that is one of the intracontinental graben systems around the Ordos Block in central China (Fig. 1a) (Zhang et al., 1998). The basin is bounded by the Qinghai–Tibet Block to the west, stable Ordos Block to the north, North China Block to the east, and Qinling Orogenic Belt and South China Block to the south (Lin et al., 2015). The Weihe Basin is irregular in shape, being narrower in the west along the Weihe River (Lin et al., 2015), and it connects with the Shaanxi Graben in the east (Fig. 1b). Since the Eocene, the basin has received sedimentary deposits up to 7000-m thick due to the uplift of mountainous blocks to the south and north of the basin (SSB, 1988; Zhang et al., 1998; Lin et al., 2015).

Geological and geophysical data indicate that many active normal faults have developed in the Weihe Basin region (e.g., Peng, 1992a; Feng et al., 2003; Tian et al., 2003; Deng, 2007; Shi et al., 2008). In southeastern parts, normal faults are characterized by a series of stepped fault scarps dipping into the basin with an average dip-slip rate of ~2 mm/yr (Rao et al., 2014; Lin et al., 2015). The slip rates of major active faults in the northern and western parts of the basin are estimated to be of the order of 0.1–0.5 mm/yr (Xu et al., 1988). These active normal faults have developed in response to pre-existing spreading and rifting of the continental crust caused by variations in lithospheric structures with respect to the neighboring Ordos Block (Lin et al., 2015). The basin has an overall tendency of movement toward the southeast with respect to the stable Eurasian Plate, which fits into the geodynamic setting of the study area (SSB, 1988; Rao et al., 2011; Rao et al., 2014; Lin et al., 2015).

Among more than 10 large historical earthquakes of ≥ M7.0 that have occurred in the graben systems around the Ordos Block, 4 have occurred in the Weihe Basin region (SSB, 1988; Deng, 2007). The most devastating earthquake was the 1556 M8.5 Huaxian earthquake in the eastern part of the Weihe Basin, which devastated 130 counties in 11 provinces and caused more than 830,000 fatalities (e.g., Kuo, 1957; Wang, 1980; SSB, 1988; Xie, 1992; CENC, 2007; Liu and Wang, 2012). Other strong earthquakes that have occurred within the Weihe Basin region include the 780 BCE M7.0 Baoji earthquake, 1501 M7.0 Chaoyi earthquake, 1556 M7.5 Yanliang earthquake, 1568 M6.8 Lintong earthquake, and 1568 M6.5 Gaoling earthquake (Lin et al., 2015) (Fig. 1c). High levels of historical seismicity and the associated focal mechanisms indicate that normal faulting in the Weihe Basin has been seismically active under the intracontinental extensional regime (e.g., SSB, 1988; Zhang et al., 1998; Deng, 2007; Rao et al., 2014; Lin et al., 2015).

3. GPS data and crustal movements

3.1. Distribution of GPS velocity fields

The main purpose behind the construction of the Crustal Movement Observation Network of China GPS monitoring network was to investigate the crustal movements and deformations of the Weihe Basin region and the surrounding areas (SMCCEA, 2013). This GPS network consists of approximately 35 campaign GPS sites that have been occupied annually and observed for at least 3 days during each survey. The GPS velocities used in the study were provided by the Second Monitoring Center of the China Earthquake Administration (SMCCEA, 2013), who processed the GPS data using the GAMIT/GLOBK software packages (King and Bock, 2000; Herring, 2002), based on the processing strategy used in both Shen et al. (2000) and Wang (2009). The station positions and velocities were estimated in the ITRF2008 reference frame (Altamimi et al., 2011) using the quasi-observation combination analysis technique (Dong et al., 1998, 2006). As the focus of this study was on the analysis of the interior crustal deformation of the Weihe Basin region, the GPS velocity solutions were further transformed into a regional reference frame with respect to the Eurasian Plate. The Eurasian Plate is a stable block located in the northwest of mainland China (Fig. 1a; Qu et al., 2014b; Kogan et al., 2000). The Euler vector of the Eurasian Plate was calculated by applying constraints that minimize the motions at 11 IGS stations distributed within the stable interiors in the ITRF2008 reference frame (SMCCEA, 2013; Wang, 2009; Shen et al., 2000). Then, the GPS velocity solutions of the Weihe Basin region with respect to the Eurasian Plate were obtained based on the Euler vector of the Eurasian plate (SMCCEA, 2013; Wang, 2009; Shen et al., 2000). The horizontal components of the GPS velocity fields together with the 95% confidence error ellipses for the periods 2001–2007 and 2008–2011 are shown in Fig. 2a and b, respectively. In addition, to investigate the change in the deformation field of the study area during the one-year period prior to the nearby May 2008 M8.0 Wenchuan earthquake (~500 km to the southwest of the study area) (Xu et al., 2010), GPS velocity fields were calculated for the period 2007–2008 (Fig. 2c). Because the 2008 GPS campaigns were conducted during mid-September, the coseismic effect of the Wenchuan earthquake was removed from the velocity field for the period 2007–2008 using the coseismic displacement field (Shen et al., 2009; SMCCEA, 2013).

Comparison of the GPS velocity field of 2001–2007 (Fig. 2a) with 2008–2011 (Fig. 2b) revealed that the entire basin had an overall tendency of movement toward the southeast with respect to the stable Eurasian Plate, which fits into the geodynamic setting of the study area (Qu et al., 2014b; Shen et al., 2009; Gan et al., 2007). The main difference is that the direction of the GPS velocity field during 2008–2011 was deflected slightly toward the east and its magnitude was slightly larger (Fig. 2b versus a). However, during 2007–2008, both the magnitude and the direction of the crustal velocity changed, especially in western and central parts of the Weihe Basin region (Fig. 2c); the magnitude was largest during 2001–2011, while the direction changed from southeastward to northeastward. Nevertheless, the overall crustal movement of the Weihe Basin region appears to have been recovering during 2008–2011, despite the short-term fluctuation (2007–2008). These features indicate that the overall crustal movement of the Weihe Basin region was temporally continuous during the observation period (2001–2007 and 2008–2011).

3.2. Differential motion fields within Weihe Basin region

Relative to the stable Eurasian Plate, the velocity field of the Weihe Basin region includes a rigid rotational component and a spatially varying component within the basin. To analyze further the interior motions within the Weihe Basin region, we calculated the differential motion field by removing the rigid rotation of the entire study area based on the solution from the Euler vector (Gan et al., 2007). The residual velocity fields (Fig. 2d–f) allow us to appreciate the spatially varying differential motions inside the basin. Additionally, because the velocity field is a vector field, the differential motion field is the vector difference. When the rigid rotation velocity is removed from the velocity field relative to the stable Eurasian Plate, the differential velocities of the GPS sites can present different directions. It should be noted that, because of the limited number of GPS sites within the basin, the trend of the differential motion field does not appear uniform. However, the strength of the crustal motions within the Weihe Basin region can be
detected from the differential motion field; thus, the changes in differential motions during the three different periods could be revealed. We found no obvious differential motion between the western and eastern parts during 2001–2007 and the magnitudes of the velocities were all small, i.e., averaging $\sim 1.3$ mm/yr (Fig. 2d). During 2008–2011, differential motions between the western and eastern parts did exist; the interior crustal activities were relatively larger in eastern parts than western parts (Fig. 2e). However, we found that the overall magnitude of interior movement of the Weihe Basin region increased considerably during 2007–2008 (Fig. 2f).

4. Strain model and significance testing

4.1. Strain model

The spatial characteristics of the crustal GPS velocity field can reveal the crustal deformation, although the reference frame might have an influence (Ward, 1994; Wu et al., 2015). Unlike velocity data, the strain rate is independent of the frame of reference. In addition, the strain rate field can describe numerically the ongoing geodynamic processes, reflect the response of the internal mechanism(s) of crustal deformation, and reveal local strain accumulation rates and their possible correlation with seismicity (Ward, 1994; Calais et al., 2000; Hori, 2003; Hackl et al., 2009; Riguzzi et al., 2012). Therefore, we used GPS observations at different periods to establish sound crustal strain models.

We employed the kinematic model (Eq. 1) to model the variations of the strain fields of the Weihe Basin. Actually, the kinematic model (Eq. 1) is the elastic motion equation that describes the total rotation and linear strain of crustal movement. This model is derived through three steps. First, in the traditional theory of plate tectonics, a block is considered a rigid body. Therefore, according to the Euler theorem for a rigid block, the block kinematic model can be defined by the Euler equation. Second, because many reports have demonstrated that some blocks are not entirely rigid (Burbidge, 2004; Nanjo et al., 2005), deformation exists not only over the boundary zones between the blocks...
but also within blocks. Hence, the crustal motion of any GPS point within a block represents the superposition of the block rotation and the differential deformation within the block. If the differential motion (or strain) within a block is homogeneous, the compound velocity vector of a point within a block can be described by the total rotation and the homogeneous strain model. Third, if the strain is uneven within a block, it can be considered a linear function of location. Therefore, there is need to model the variable strain within the block. Then, the total motion of any point within a block can be obtained by including the motion due to the rigid rotation and the motion due to the uneven strain within a block, which is the total rotation and linear strain model (Eq. 1). Detailed descriptions of Eq. (1) can be found in Qu et al. (2014b):

\[
\begin{bmatrix}
V_x \\
V_y \\
V_z
\end{bmatrix}
= \begin{bmatrix}
- r \sin \phi \cos \lambda - r \sin \phi \sin \lambda \cos \phi & r \cos \phi & r (\lambda - \lambda_0) \cos \phi & r (\phi - \phi_0) \\
- r \sin \phi \sin \lambda & r \cos \phi & r (\lambda - \lambda_0) \cos \phi & r (\phi - \phi_0) \\
- r \cos \phi & 0 & 0 & 0
\end{bmatrix}
+ \begin{bmatrix}
\omega_x \\
\omega_y \\
\omega_z
\end{bmatrix}
+ \begin{bmatrix}
A_0 \\
B_0 \\
C_0
\end{bmatrix}
\begin{bmatrix}
\lambda \\
\phi
\end{bmatrix}
\]

where \( V_x \) and \( V_y \) are the eastern and northern components of the velocity vector of any point within the study region, respectively; \( \lambda, \phi \) are the longitude and latitude of the point; \( r \) is the average radius of the Earth; \( \omega_x, \omega_y, \) and \( \omega_z \) are the components of the Euler vector; \( \chi, \) \( \eta, \) \( \zeta, \) \( \xi, \) \( \eta, \) \( \zeta, \) \( \xi, \) \( \eta, \) \( \zeta, \) \( \xi \) are the strain parameters. Here, \( A_0, B_0, \) \( C_0 \) are the linear terms of the strain parameters that describe the homogeneous strain features, and the terms \( \xi, \eta, \zeta, \) \( \xi, \) \( \eta, \) \( \zeta, \) \( \xi, \) \( \eta, \) \( \zeta, \) and \( \xi \) are the quadratic terms of the strain parameters that characterize the uneven strain features.

4.2. Applicability and significance testing

Errors in GPS measurements could affect the calculated strain parameters in the kinematic model. Statistical significance hypothesis testing can minimize the GPS errors and provide realistic strain parameters for characterizing the crustal deformation features of the Weihe Basin region. In this study, we performed significance hypothesis testing on the quadratic terms of the strain parameters in Eq. (1), which can fully represent the nature of the uneven strains. Then, from a statistical point of view, we could determine the quadratic terms of the strain parameters as true or false under the given significance level. Accordingly, Eq. (1) can be expressed in matrix form as follows:

\[
\begin{bmatrix}
V_x \\
V_y \\
V_z
\end{bmatrix}
= \begin{bmatrix}
A & B
\end{bmatrix}
\begin{bmatrix}
X \\
Y
\end{bmatrix}
\]

where:

\[
A = \begin{bmatrix}
- r \sin \phi \cos \lambda - r \sin \phi \sin \lambda \cos \phi & r \cos \phi & r (\lambda - \lambda_0) \cos \phi & r (\phi - \phi_0) \\
- r \sin \phi \sin \lambda & r \cos \phi & r (\lambda - \lambda_0) \cos \phi & r (\phi - \phi_0) \\
- r \cos \phi & 0 & 0 & 0
\end{bmatrix}
\]

\[
X = \begin{bmatrix}
\omega_x \\
\omega_y \\
\omega_z \\
A_0 \\
B_0 \\
C_0
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
x^2 & 0 & 0 & 0 & 0 \\
0 & 0 & x^2 & y^2 & xy \\
0 & x^2 & y^2 & xy & 0
\end{bmatrix}
\]

\[
Y = \begin{bmatrix}
\xi_1 \\
\xi_2 \\
\xi_3 \\
\xi_1 \\
\xi_2 \\
\xi_3
\end{bmatrix}
\]

Equation (2) can be regarded as an adjustment model with additional system parameters; vector \( X \) consists of the main parameters of the equation including the Euler vector and the linear terms of the strain parameters, while vector \( Y \) is the added system parameter consisting of the quadratic terms of the strain parameters.

Equation (2) can be further rewritten as follows by applying the method of linear hypothesis testing (Koch, 1980; Tao, 2007):

\[
\begin{align*}
\Delta_{2n \times 1} &= \begin{bmatrix} X_{1n} \\ X_{2n} \end{bmatrix} - l, \quad \Pi = (A_{2n \times 6}, B_{2n \times 6}) \\
H_{1n} &\begin{bmatrix} \mathbf{X} \\ \mathbf{Y} \end{bmatrix} = 0, \quad H = (0_{n \times 6}, J_{n \times 6})
\end{align*}
\]

where the linear hypothesis is \( H_0: \mathbf{Y} = 0 \), \( \Delta \) is the residual error of the velocity component, \( l = \begin{bmatrix} V_x \\ V_y \end{bmatrix} \), \( n \) is the number of GPS stations in the study region, and \( I \) is the identity matrix.

After \( H_0 \) is set up, the \( F \) test is constructed as:

\[
F = \frac{R/\text{rank}(H)}{T/(2n - \text{rank}(A))} \sim F_{(\text{rank}(H), 2n - \text{rank}(A))}
\]

That is,

\[
\frac{\hat{\mathbf{Y}}^\top Q^{-1} \hat{\mathbf{Y}} / s}{T/(2n - 12)} \sim F_{(6, 2n - 12)}
\]

The reject region is:

\[
F > F_{(6, 2n - 12)}
\]

where \( \text{rank}() \) in Eq. (7) is the rank of \( H, Q \) in Eq. (8) is the inverse of the weighting matrix for \( \hat{\mathbf{Y}}^\top \hat{\mathbf{Y}} / s \) in Eq. (8) is the sum of the residual squares, and \( s \) in Eq. (9) is the given significance level.

If \( H_0 \) is rejected under a significance level of \( \alpha \), it is reasonable to consider that the quadratic terms of the strain parameters are significant. If \( H_0 \) is accepted (i.e., Eq. (9) is false), it can be considered that the quadratic terms of the strain parameters are not significant. Using the GPS observations, we conducted linear hypothesis tests to determine the significance of the quadratic terms of the strain parameters (Table 1). It can be seen from Table 1 that the null hypothesis was rejected for the periods 2001–2007, 2008–2011, and 2007–2008, and that the \( F \) values for the three periods are all larger than the reference critical value. These findings indicate that the quadratic terms of the strain parameters were all relatively significant under a significance level of \( \alpha = 0.1 \). Thus, Eq (1) can be considered a reasonable model with which to represent the deformation–strain characteristics of the Weihe Basin region.

5. Results and discussions

To obtain the principal strain axes and the maximum shear strain rates, we first calculated the strain parameters \( (A_0, B_0, C_0, \xi_1, \xi_2, \xi_3, \zeta_1, \zeta_2, \zeta_3) \) using the total rotation and linear strain model (Eq. 1) based on the GPS velocity fields shown in Fig. 2a–c. Then, we calculated the linear and shear strains in the east–west and the north–south directions, respectively (Li et al., 2007). The maximum shear strain rates and the principal strain rates could be obtained based on the linear and shear strains. Finally, we obtained the principal strain rates (including their directions) at each GPS site in the Weihe Basin based on Eq. (1) (Li et al., 2007; Qu et al., 2014b).

5.1. Variations of the principal strain fields and their evolution tendency

Vector maps of the principal strain rates at each GPS site in the Weihe Basin region for the periods 2001–2007, 2008–2011, and 2007–2008 are shown in Fig. 2a–c. Table 1 shows the significance hypothesis testing of the quadratic terms of strain parameters of the Weihe basin region during the different periods.

<table>
<thead>
<tr>
<th>Time periods</th>
<th>( F ) value</th>
<th>Reference critical value (significance level = 0.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001–2007</td>
<td>6.02</td>
<td>1.87</td>
</tr>
<tr>
<td>2008–2011</td>
<td>2.20</td>
<td>1.90</td>
</tr>
<tr>
<td>2007–2008</td>
<td>2.23</td>
<td>1.89</td>
</tr>
</tbody>
</table>

The results indicate that the principal strain rates and the maximum shear strain rates were all larger than the reference critical values in the Weihe Basin region for the periods 2001–2007, 2008–2011, and 2007–2008.
while eastern areas displayed significant extensional strain rates. The opposite arrow represents the extensional principal strain rate, while the crossed arrow represents the compressional principal strain rate. The black thick dotted lines indicate the scope of the Weihe basin (Peng, 1992b).

Fig. 3. Vector maps of the principal strain rates of the Weihe basin region for the periods of 2001–2007 (Fig. 3a), 2008–2011 (Fig. 3b) and 2007–2008 (Fig. 3c), respectively (unit:10^{-8} /yr). The black cross arrows indicate the principal strain rate vectors. The length and the direction of the arrow represent the magnitude and the principal direction of the principal strain rate, respectively. The opposite arrow represents the extensional principal strain rate, while the crossed arrow represents the compressional principal strain rate. The black thick dotted lines indicate the scope of the Weihe basin (Peng, 1992b).

2007–2008 are shown in Fig. 3a–c, respectively.

The spatial features of the principal strain fields during 2001–2007 (Fig. 3a) and 2008–2011 (Fig. 3b) were found similar; western parts of the Weihe Basin region possessed certain compressional strain rates, while eastern areas displayed significant extensional strain rates. However, some differences in the principal strains existed between the two periods. During 2001–2007 (Fig. 3a), the compressional strain rates in the western Weihe Basin region mainly presented in the NEE–SWW direction with a mean strain rate of about $-0.9 \times 10^{-8}$ /yr, whereas they were deflected slightly northward with a mean strain rate of about $-1.2 \times 10^{-8}$ /yr during 2008–2011 (Fig. 3b). Comparison of Fig. 3a and 3b reveals that the magnitude of the extensional strain rates in the western Weihe Basin region decreased from 2001 to 2007 to 2008–2011, as indicated by the relatively shorter black arrows. Central and eastern parts of the Weihe Basin region mainly presented extensional strain rates in the NW–SE direction (Fig. 3a). Although these areas mainly displayed extensional strain in the NW–SE direction during 2008–2011, the compressional strain rates increased over the 2001–2007 level. However, during 2007–2008, western parts of the Weihe Basin region mainly presented compressional strain rates in the approximate NE–SW direction (Fig. 3c versus a and b), with a mean compressional strain rate of about $-4.4 \times 10^{-8}$ /yr. The compressional strain rates in central parts of the Weihe Basin region also increased during 2007–2008 (Fig. 3c versus a). In contrast, eastern parts of the Weihe Basin region mainly presented significant and increased extensional strain in the NW–SE direction, with the extensional strain axes deflected counterclockwise by $\sim 13^\circ$ from the orientation during 2001–2007 (Fig. 3c versus a).

According to the variation characteristics of the principal strain fields, we conclude that despite the variations of the principal strain rates of the Weihe Basin region, especially in western parts during 2007–2008, the general features of the principal strain fields remained unchanged during the long term (Fig. 3b versus a). In addition, in accordance with the considerably increased compressional strain in the NE–SW direction in western parts during 2007–2008 (Fig. 3c), we further infer northeastward extrusion of the crust attributable to the May 2008 Wenchuan earthquake. Furthermore, this dynamic effect might have gradually permeated to eastern parts of the Weihe Basin region during 2008–2011, causing increased compressional strain rates and relatively intensive interior motions (Fig. 3b and c).

Relatively significant compressional strain in the NE–SW direction was predominant over the western Weihe Basin region, while obvious extensional strain in the NW–SE direction prevailed over the eastern Weihe Basin region (Fig. 3a–c). This feature is consistent with the stress–strain characteristics of the Weihe Basin region simulated using the finite element model based on geological and geophysical surveys (Zhang et al., 2011). The numerical simulation results showed that the western Weihe Basin mainly presents compressional strain, while central and eastern areas of the basin mainly present extensional strain in the NW–SE direction. The regional stress–strain fields inferred from the earthquake composite focal mechanisms also showed that the dominant extensional stress–strain axis is in the NW–SE direction (in central and eastern parts of the basin), while the compressive axis is in the NE–SW direction (in the western basin) (SSB, 1988; Song, 1989; Wang, 2010). Additionally, the stress–strain fields inverted from borehole stress measurements (Xie et al., 1991) and fault slip data (Peng, 1992a) have all indicated the same characteristics as our derived strain fields.

By analyzing the formation of the Weihe Basin, we understand that the regional stress–strain field has mainly undergone three important episodes of evolution: early Tertiary, Miocene, and Pliocene–Quaternary (Zhang et al., 2003). In the early Tertiary period, i.e., the formation stage of the basin, the principal stress field presented tensile stress in the NWW–SEE direction. In the Miocene period during the development stage of the basin, the basin presented characteristics of right-lateral shearing activity. The direction of extensional stress was deflected from NW–SE to NE–SW. However, in the Pliocene–Quaternary, the basin presented characteristics of left-lateral shearing activity. The stress field of the basin mainly presented a tensile stress field in the NW–SE direction with certain compressional stress in the NE–SW direction. Therefore, after undergoing the above three important evolutionary episodes, the current tectonic deformation characteristics of the Weihe Basin were finally formed. The principal strain axes are considered to represent the current tectonic stress field (Fig. 3a–c). The
common spatial features of the principal strain axes during the different periods all show that western parts of the Weihe Basin region possessed significant extensional strain. This characteristic of the principal strain axes is consistent with the recent geodynamic background of the region. The compressional strain axes acting at the western part of the Weihe Basin might be attributable to the effects of the India–Eurasia collision and the associated resistance of the Alashan and Ordos blocks (Liu et al., 2007; Bai et al., 2010; White and Lister, 2012). The collision is causing the crustal material of the Qinghai–Tibet Plateau to move toward the east (Bai et al., 2010). The encounter of the eastward-moving crust with the Alashan and Ordos blocks results in a compressional regime in western parts of the Weihe Basin region. In central and eastern parts of the Weihe Basin region, the prevailing extensional strain axes might be attributable to eastward slab rollback (Schellart et al., 2007; Royden et al., 2008), reduction in the rate of Pacific–Eurasia plate convergence (Northrup et al., 1995), or subduction of the Philippine Sea Plate from the southeast (Wakita et al., 2013). The result of these dynamic effects is the eastward expansion of mainland China (Zhang et al., 1998, 2003; Wang et al., 2012; Zhou et al., 2015; Li et al., 2016). Hence, extensional strain axes are dominant in central and eastern parts of the Weihe Basin region.

An interesting phenomenon between the principal strain axes and the distribution of ground fissures can be seen in Fig. 3a–c. The ground fissures in the Weihe Basin are distributed mainly in several bands in central and eastern parts of the basin where extensional strain prevails. It indicates that the formation and the development of ground fissures are caused primarily by the activity of tectonic faults and that they are closely related to the regional tectonic stress field. In the short term (tens to hundreds of years), the strain inside the plate is close to the elastic strain; thus, the stress–strain field in the plate follows the elastic constitutive law and the principal stress axis coincides with the principal strain axis at any point (Reynolds et al., 2002). The direction of tensile strain is approximately vertical to the faults (and ground fissures), showing that tensile stress drives the development of the numerous ground fissures (Zhang et al., 2011). Furthermore, the difference in the tectonic strain field is also the fundamental reason for the heterogeneous development of ground fissures in eastern and western parts of the Weihe Basin (Zhang et al., 2012).

5.2 Variations of the maximum shear strain and their correlation with seismicity

The magnitude of the shear strain rate reflects the degree of crustal deformation, i.e., the higher the shear strain rate, the more severe the crustal activity. Generally, higher rates of strain accumulation should be associated with larger or more frequent earthquakes (Segall, 2010). To obtain the spatial distribution of maximum shear strain rate for analysis of its correlation with seismicity, the maximum shear strain rates will be combined to explore the mechanism(s) of earthquakes in the Weihe Basin region. This might indicate that the increased earthquake activity in western parts of the Weihe Basin region was influenced by the Wenchuan earthquake, which also caused short-term compressional strain fields in this region (Figs. 3c and 4c).

It should be noted that the postseismic effect of the Wenchuan earthquake was not considered in the GPS velocities during the period 2008–2011. According to Ding et al. (2013), the main postseismic displacements were concentrated within ~50 days after the mainshock and they rapidly decayed with distance (Cui et al., 2016). Therefore, it was considered that the postseismic displacements did not exert great influence on the average velocities (2008–2011) in our study area. If there were continuous GPS or other geodetic observations, we could further distinguish the detailed deformation information to enhance the results presented here. Furthermore, we analyzed only the correlation between seismicity and maximum shear strain rates based mainly on the degree of crustal activity. In fact, the processes of the development and the occurrence of earthquakes are complex. In future work involving the seismology and a suitable focal mechanism, inversion methods will be combined to explore the mechanism(s) of earthquakes in the Weihe Basin region.

The strain results obtained in this study showed no obvious correlation with the faults. The main purpose behind the construction of the GPS monitoring network was to investigate regional crustal movements and deformations of the Weihe Basin and surrounding areas. The GPS sites are positioned in reasonably stable areas far from any fault zone (Fig. 2). Therefore, although the GPS velocity fields can represent regional crustal movements, there are too few GPS sites near faults to characterize their movements. In addition, the numerical finite element analysis method showed the current average velocity of the regional faults is about 1 mm/yr (Qu et al., 2017). Therefore, there is no obvious relationship between the strain field and the faults. If the network of GPS sites was denser across the faults, the correlation between the crustal deformation characteristics calculated by the GPS velocities and the activity of the tectonic faults might be elucidated.
Fig. 4. Contour maps of the maximum shear strain rates (unit: $10^{-8}$/yr) and the distribution of earthquakes over the Weihe basin region, during the periods of 2001–2007 (Fig. 4a), 2008–2011 (Fig. 4b) and 2007–2008 (Fig. 4c), respectively. The detailed seismic statistical records are from the Shaanxi Seismic Information Network and the China Seismic Network (http://www.ceic.ac.cn, http://www.eqsn.gov.cn).

Fig. 5. The distribution of earthquakes in 2008 in the Weihe basin region before and after the Wenchuan earthquake from January to April (Fig. 5a) and from May to August (Fig. 5b) in 2008, respectively. The epicenter of the main Wenchuan earthquake event occurred approximately 500 km to the southwest of the study area.
Finally, the strain features presented here are consistent with the recent geodynamic background, geological and geophysical surveys (discussed in Section 5.1), and the formation mechanism of tectonic ground fissures. In addition, the GPS measurements provide important insight for investigating active deformation of the crust. Because the GPS data record indicates a predominantly interseismic strain pattern, one must wonder about the location of the release of the GPS-predicted strain. The Weihe Basin is an active basin in which several great historic earthquakes have occurred. This indicates that active deformation of the crust should be reasonably strong within the basin. Consequently, our results showed that the highest values of active deformation were found mostly within the Weihe Basin.

6. Conclusions

This study used GPS observations from yearly campaigns during 2001–2011 to analyze the variations of the crustal deformation and the strain field of the Weihe Basin region. Despite some fluctuation in the degree of crustal movement in the short term, the overall crustal movement of the entire Weihe Basin region was found temporally continuous during our observation period. The entire Weihe Basin region exhibited an overall tendency of movement toward the southeast with respect to the stable Eurasian Plate. Although the principal strain rates of the Weihe Basin region showed some short-term variations, the overall features of the principal strain field were not altered in the long term. It was found that western and eastern parts of the Weihe Basin region presented compressional and extensional strains, respectively.

We found correlation between the maximum shear strain field and the distribution of seismicity, i.e., regions with high shear strain were also areas with frequent earthquakes. In addition, there was an obvious increase in seismicity in western parts of the Weihe Basin region during May–August 2008 following the Wenchuan earthquake.

According to the variation characteristics of the crustal deformation and the strain fields, we inferred that western parts of the Weihe Basin region might have been affected during 2007–2008 by a northeastward extrusion caused by the Wenchuan earthquake. However, over time, this dynamic effect might have gradually permeated to eastern parts of the Weihe Basin region during 2008–2011. The findings of this study will enhance the understanding of the current tectonic deformation characteristics and recent geodynamic processes of the Weihe Basin region. Our future studies will continue the monitoring of the crustal movements in the study region using GPS technology (additional continuous GPS) and other monitoring sensors such as interferometric synthetic aperture radar, gravity monitoring, and leveling techniques to improve the resolution and accuracy of the monitoring capability.

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