Strain Transformation Adjacent to the West Qinling Orogen: Implications for the Growth of the Northeastern Tibetan Plateau

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The West Qinling orogen has played an important role in accommodating the deformation in the northeastern Tibetan Plateau induced by the India-Eurasia convergence. Here we construct a vertical land motion (VLM) model based on the latest leveling observations adjacent to the West Qinling orogen. Combined with the horizontal deformation field, the crustal deformation pattern in this area is investigated. Additionally, slip rate and coupling coefficients of the West Qinling fault, the longest fault separating the West Qinling orogen from the Lanzhou (Longxi) block, are inverted and constrained with GPS and VLM observations. Results show that the West Qinling fault slips slowly at a rate of 1–2 mm/yr and is strongly coupled with a moment magnitude deficit of Mw7.4. The crustal uplift rates adjacent to the West Qinling orogen are 0–3 mm/yr; which combined with 0–12.5 × 10−9/yr contraction rates, suggests that strain transformation plays a key role in controlling the tectonic uplift in the West Qinling orogen, and furthers our understanding of the contemporary geomorphic and topographic features. We identify a significant deformation transition belt at longitudes of 105°–106°E, which indicates that crustal deformation, induced from the northeastern expansion of the Tibetan Plateau, is mainly constrained to the plateau, rather than accommodated by crustal materials escaping eastward along the Qinling Mountains.

Keywords: the west qinling orogen, strain transformation, vertical land motion, leveling observations, moment deficit

HIGHLIGHTS

1. A vertical land motion model adjacent to the West Qinling orogen is constructed based on leveling observations.
2. Strain transformation plays an important role in controlling the tectonic uplift in the West Qinling orogen.
3. The West Qinling fault has a moment magnitude accumulation of Mw7.4, and thus exhibits high seismic risk.
INTRODUCTION

Strain patterns adjacent to convergent plate boundaries, especially along continent-continent collision zones such as the Tibetan Plateau and Anatolian Plateau, remain a source of active investigation (England et al., 1985; Tapponnier, 2001; Rellinger et al., 2006). Known as the “roof of the world,” the Tibetan Plateau is famous for its high average elevation of 4,000 m, as well as complex tectonics and deformation patterns that are driven by the India-Eurasia convergence (Molnar & Tapponnier, 1975; Tapponnier et al., 1982; Tapponnier, 2001). Horizontal contraction and vertical uplift/thickening of the crust have been shown to be the primary method to accommodate deformation between the late Cretaceous and Miocene in the Tibetan Plateau (Chung et al., 1998; Ruddiman, 1998; Royden et al., 2008). Since the middle Miocene, the Tibetan Plateau has exhibited expansion and outward growth (Molnar & Tapponnier, 1975; Royden, 1997, 2008). Contemporary GPS observations identify two significant expansion passages blocked by the Sichuan Basin: 1) the southeastward extrusion around the eastern Himalaya Syntaxis (EHS) despite its dynamic mechanisms and 2) the north-/east-/northeast-ward growth (Zhang et al., 2004; Gan et al., 2007; Wang & Shen, 2020). Unlike the clear extrusion in the southeastern Tibetan Plateau (Bai et al., 2010; Bao et al., 2015; Li et al., 2020; Wang & Shen, 2020), the expansion passage and strain pattern are still under debate within the northeastern Tibetan Plateau.

There are two leading models to explain the expansion and deformation pattern of the northeastern Tibetan Plateau. One model highlights the significance of the eastward extrusion of the crustal materials, which considers the Qirenling orogen as the channel for the eastward escape of the plateau materials (Tapponnier, 2001; Ma et al., 2013; Yu & Chen, 2016). The other model suggests bookshelf faulting, governed by the large-scale sinistral Haiyuan and Kunlun faults and the dextral Riyueshan and Elashan faults, in which the deformation induced from the northeastward/eastward extrusion of Tibetan Plateau is confined to the plateau and accommodated by complex crustal deformation (i.e., block rotation and tectonic uplift), adjacent to the West Qinling orogen, Qilian, and Liupanshan regions (Cheng et al., 2015; England & Molnar, 1990; Hao et al., 2021; Kirby et al., 2007; Kirby & Harkins, 2013; Li Y. et al., 2018; Zheng et al., 2016; Zuza and Yin, 2016).

Therefore, the West Qinling orogen is pivotal to understand the strain pattern in the northeastern Tibetan Plateau. Previous studies, based on dense horizontal GPS velocities and active tectonics, suggest that the crustal deformation in West Qinling orogen is characterized by crustal contraction, mountain uplift, diffuse deformation, and basin formation (Hao et al., 2021; Kirby et al., 2007; Li Y. et al., 2018; Zheng et al., 2016). However, vertical crustal motions have not been thoroughly investigated, hindering further understanding of the deformation pattern in this region. Hao et al. (2016) proposed a vertical velocity field around the Ordos block, which is inferred from precise leveling observations with a lack of concentration on the contemporary deformation in the West Qinling regions. Additionally, the direct explanation of leveling vertical velocities might be misleading due to the influence of local non-tectonic factors (Hammond et al., 2016; Hao et al., 2016; Hammond et al., 2019).

In this study, a vertical land motion (VLM) model is constructed using a robust imaging method (Hammond et al., 2016; Kreemer et al., 2020) and leveling observations from Hao et al. (2016) with new observations from recent field work. The slip rate and locking coefficients of the West Qinling fault, the longest active fault in West Qinling orogen, are calculated with the GPS velocity field from Hao et al. (2021), and our VLM model. Additionally, the deformation pattern is analyzed based on the 3-D deformation model. This study provides new evidence of strain transformation between horizontal contraction and vertical uplift, which furthers our understanding of the strain pattern in the northeastern Tibetan Plateau.

TECTONIC SETTING

The West Qinling orogen separates the North China block and Lanzhou block from the South China block and Songpan-Ganzi Terrane (Figures 1A,B, Zheng et al., 2010), and is also recognized as the step-over of the large-scale sinistral Haiyuan and Kunlun faults (Figure 1; Yuan et al., 2004), which control the deformation pattern in the northeastern Tibetan Plateau (Kirby et al., 2007; Duvall & Clark, 2010; Yuan et al., 2013; Cheng et al., 2014; Zuza and Yin, 2016). Two small-scale active fault zones, exhibiting low levels of slip, are found along the West Qinling orogen, including the NWW-trending sinistral and NEE-trending dextral fault systems, which signal the diffuse deformation and slip transference along the east end of the Kunlun fault (i.e., Zheng et al., 2016; Zheng et al., 2013).

As the northern boundary of the West Qinling orogen, the nearly W-E striking sinistral West Qinling fault, with a length of ~600 km, separates the Lanzhou (Longxi) block from the West Qinling orogen (Figure 1B). The West Qinling fault has experienced a long evolutionary history since the Paleogene. It was initiated as a frontal thrust fault (Clark et al., 2010), and reactivated in the late Quaternary (Li et al., 2007). Field investigations and structural geological data, identify slip rates of ~2.5–2.9 mm/yr (Chen & Lin, 2019), 0.71 ± 0.18 mm/yr (Zheng et al., 2016), and ~2.3 ± 0.2 mm/yr (Li et al., 2007) since the Pleistocene. However, contemporary geodetic data indicates slip rates of <1 mm/yr (Hao et al., 2021; Li Y. et al., 2018). Seismic records show that no major earthquakes occurred along the West Qinling fault in the past ~300 years since the 1718 M7.5 Tongwei earthquake.

DATA AND METHODS

GPS horizontal velocities were collected from Hao et al. (2021). The data were obtained from the Crustal Movement Observation Network of China (CMONOC), the National GPS Geodetic Control Network of China (NGGCNC), and the Gansu Bureau of Surveying Mapping and Geoinformation (GBSMG). Parts of the NGGCNC stations were resurveyed by the China Earthquake Administration (CEA) and the Second Monitoring
and Application Center (SMAC). First, the GAMIT package (Herring et al., 2015a) was utilized to process all raw GPS data, containing ~70 International Terrestrial Reference Frame (ITRF) core stations, to obtain loosely daily solutions of satellite orbits, station coordinates, tropospheric zenith delays, and their co-/variances. The geophysical models and parameters used in data processing are shown in Table S1. Second, the GLOBK software (Herring et al., 2015b) was utilized to combine the regional and global daily solutions to estimate station positions and uncertainties, and to convert the loosely daily solutions into the ITRF 2014 (Altamimi et al., 2017). Third, GPS position time series were contaminated by the 2008 Ms 8.0 Wenchuan and 2011 Ms 9.0 Tohoku-Oki earthquakes (Wang & Shen, 2020). The coseismic displacements from Shen et al. (2009) and Hao and Zhuang, (2020) were therefore interpolated onto GPS sites by utilizing the Kriging method and were used to correct the position time series. Considering the postseismic deformation of the 2008 Ms 8.0 Wenchuan earthquake, GPS data measured before 2008 are used for those stations within the postseismic deformation region determined by Wang & Shen (2020). The postseismic deformation of the 2011 Tohoku-Oki earthquake is not significant within our study area, and is thus disregarded. Finally, GPS velocities with respect to ITRF2014 were fitted from the corrected GPS position time series using a linear function (Equation 1) and weighted least squares. Here \( x(t) \) is the site position time series; \( x_0 \) is the initial position at time \( t_0 \); \( v \) represents station velocity, and \( D_i \) is the coseismic (or equipment changes) step at time \( t_i \); \( H(t-t_i) \) is the Heaviside function; \( n_c \) is the number of earthquakes and equipment changes. Data are then transformed into a regional reference frame with respect to the stable Ordos block using the rotation pole of (75.083°N ± 0.850°, 139.692°W ± 3.701°, 0.352 ± 0.006°/Ma) (Figure 2A) provided by Hao et al. (2021).

\[
x(t) = x_0 + v(t-t_0) + \sum D_i H(t-t_i)
\]

Parts of the leveling data in Hao et al. (2016) are included. First-order leveling observations were also collected from the National Administration of Surveying, Mapping and Geoinformation (NASMG) resurveyed in 2013, and 500 km leveling routes in the west of the Ordos block observed in 1985/1986/1994 and resurveyed in 2017 and 2018. Vertical velocities (Figure 2B) were calculated following Hao et al. (2016), with 37 stable continuous GPS vertical velocities utilized during leveling adjustment to define the reference frame and to reduce systematic errors accumulated during leveling routes (see Hao et al. (2016) for more details). Since the leveling data are sensitive to local environmental effects, such
as groundwater changes and human activities (Hammond et al., 2016; Hao et al., 2016), we therefore despeckle the velocities with GPS-Imaging, which is robust against outliers, to construct a spatially smoothed VLM model (Hammond et al., 2016; Kreemer et al., 2020; Figures 3B, Supplementary Figure S1).

RESULTS

Horizontal Deformation From GPS Observations

The GPS horizontal velocity field, with respect to the Ordos block, identifies NNE-directed crustal movement, with significant velocity gradients adjacent to the sinistral Haiyuan and Kunlun faults but not along the West Qinling fault (Figure 2A), which suggests large horizontal differential motions along the former faults. Moreover, the velocity vectors decrease significantly to the east of 105°–106°E. To investigate these large velocity gradient belts, the strain rate field is calculated utilizing the Median Estimation of Local Deformation (MELD) algorithm, which is robust against outliers and provides realistic uncertainties (Kreemer et al., 2018, 2020). MELD requires two parameters to calculate the strain rates at grid points from the multivariate median of a set of strain rates from a number of station-based local triangles. The first parameter is the minimum number of the triangles ($N_{\text{min}}$), which we set here to be $N_{\text{min}} = 56$, meaning as few as 6 stations can be used to calculate strain rates. The second parameter is the maximum allowed value of $\sigma_{\text{max}}$, which is based on the theoretical standard deviation in the strain rate for a triangle of stations, based on the triangle’s geometry and size. This parameter is used to exclude triangles that are too small and skinny and would be detrimental to the results (Kreemer et al., 2018, 2020). We use $\sigma_{\text{max}} = 15 \times 10^{-9}$/yr, which is chosen to calculate the strain rates with a minimum theoretical spatial resolution of ∼40 km (Figure 3D).

The maximum shear strain rates are 0–30 $\times$ 10$^{-9}$/yr with the largest value existing along the Haiyuan and Kunlun faults (background in Figure 3A). These results are consistent with those of Hao and Zhuang (2020) and Wang & Shen (2020). The dilatation strain rates are $-15$–15 $\times$ 10$^{-9}$/yr and are dominantly characterized by contraction, with the peak values appearing along the West Qinling and the Qilian orogens (Figure 3B). The principal strain rates are oriented with E-/NE-directed contraction and N-/NW-directed extension (Figure 3A). In addition, strain rates significantly decrease to the east of 105°–106°E (similar with the GPS velocity field, background in Figures 3A,B), which may identify the significant deformation regions accommodating the outward expansion of the northeastern Tibetan Plateau (at least in the upper crust) resulting from India-Eurasia convergence being blocked by the rigid Ordos block. The rotation rates in Figure 3C (background color) show the clockwise rotation of the West Qinling orogen and the Lanzhou (Longxi) sub-blocks and the anticlockwise rotation of the sub-blocks adjacent to the Haiyuan and Kunlun faults, which are required by the book-shelf kinematic model (i.e., Zuza and Yin, 2016; Cheng et al., 2021).

Vertical Land Motion

The proposed VLM model in Figure 3B, Supplementary Figure S1 shows that the northeastern Tibetan Plateau uplifts at a rate of 0–3 mm/yr, except for the northeastern portion of the east
Lanzhou sub-block (ELZB), where a series of Cenozoic pull-apart basins are present (e.g., the Tianzhu and Ganyanchi basins) due to the sinistral strike-slip of the Haiyuan fault (Tian et al., 2002). The largest uplift rates appear along the Liupanshan fault, which is regarded as the northeastern margin of the outward expansion of the Tibetan Plateau (Li et al., 2017; Du et al., 2018), and the transpressional structure of the Haiyuan active fault to accommodate its sinistral motions (Zheng et al., 2013). Meanwhile, substantial uplift is observed between the central and eastern segments of the West Qinling orogen and the ELZB block, accompanied by large horizontal compression (Figure 3B). In the western Lanzhou block (WLZB), the uplift rate is much

![Figure 3](image-url)
smaller than that in the ELZB block, which indicates that the strong contraction along the Lajishan fault (LJSF) is transmitted to the Maxianshan fault (MXSF) and/or even further east. The uplift rates along the northern side of the Haiyuan fault are 1–2 mm/yr.

Rigid Block Rotation, Fault Coupling, and Block Internal Deformation

We simultaneously estimate the angular velocities and permanent strain rates within the (sub-) blocks and fault locking parameters of the West Qinling fault using the TDEFNODE program (McCaffrey et al. (2007)). To accomplish this, the study area is divided into seven small (sub-) blocks according to the distribution of active faults and seismicity (Figures 1, 2A): 1) the Ordos block (ORDB, regarded as the reference frame in our inversion), 2) the WLZB, 3) the ELZB, 4) the Alxa block (ALXB), 5) the West Qinling block (WQLB), and 6) the smallest block between the Haiyuan and Xiangshan-Tianjingshan faults (HXTB). Slip vectors (V) of the active fault can be calculated from the angular velocities of adjacent blocks.

In TDENODE, the interseismic elastic deformation adjacent to the fault is denoted by \( \phi \) (the locking coefficient), which is a purely kinematic, unitless quantity, that represents the instantaneous, spatially averaged creep fraction. \( \phi = 0 \) signifies a fully creeping fault, while \( \phi = 1 \) indicates a completely locked fault. A \( \phi \) value between 0 and 1 suggests that the fault is partially locked. Faults are represented in 3-D by nodes distributed on the surface, which is parameterized by longitude, latitude, and depth. The values of \( \phi \) and slip deficit, defined as \( \phi V \), are calculated at each node.

Block angular velocities, average strain rates, and fault coupling coefficients (\( \phi \)) are determined using the non-linear simulated annealing and grid search approaches constrained with geodetic observations (McCaffrey et al., 2007). The goodness of fit of a particular set of parameters is based on the reduced \( \chi^2 \) statistics (Eq. 2):

\[
\chi^2_n = (N - P)^2 \sum_{i=1}^{N} p_i,
\]

where \( N \) is the number of observations, \( P \) is the number of free parameters, and \( p_i \) is the misfit penalty function defined by the ratio between the data fitting residuals and data uncertainties. In the inversion, 279 horizontal GPS vectors and 514 vertical rates, derived from leveling observations, are used.

The \( \chi^2 \) values are 1.03 and 2.1 for the horizontal GPS and vertical velocities respectively, with residuals of horizontal GPS and vertical leveling velocities smaller than 2 mm/yr (Supplementary Figure S2). These values are similar to the observed data standard deviations and suggest reliable inversion results. TDEFNODE can only remove an average regional uplift and model uplift due to the locking on the faults (McCaffrey, 2005), resulting in a poor fit to the vertical velocities.

Similar to the strain rates calculated from MELD (dark green arrows in Figure 3A). Our results identify clockwise rotations of the ELZB, WLZB, and WQLB relative to the ORDO block with rotation rates of \(-0.028\degree/\text{Myr}, -0.063\degree/\text{Myr}, -0.040\degree/\text{Myr}\) (green fans in Figure 3C, with negative value indicating clockwise rotation), with the exception of the ALXA block. Figures 4A,B show the locking coefficients and slip deficit of the West Qinling fault. Average locking depths of the West Qinling fault are 6.6, 6.8, and 6.1 km from west to east with slip deficits of 1.2 mm/yr, 1.1 mm/yr, and 1.1 mm/yr respectively. In Figures 4, the regions of strongest coupling are located within the central and the western segments of the West Qinling fault, suggesting high seismic risks (Ma et al., 2017).

**DISCUSSION**

Slip Rates and Seismicity of the West Qinling Fault

Slip rates of 1.5 ± 0.4 mm/yr to 1.7 ± 0.3 mm/yr are identified for the West Qinling fault, which are larger than previous geodetic and geologic evidence-based estimates of 0.4 ± 0.3 mm/yr (Hao and Zhuang, 2020), 0.71 ± 0.18 mm/yr (Zheng et al., 2016), and 0.8 mm/yr (Li Y. et al., 2018). However, these values are smaller than the geologically derived slip rates of 2–3 mm/yr (Li et al., 2007; Chen & Lin, 2019). Slip rates of the West Qinling fault are far smaller than other NWW-directed sinistral active faults within the region, such as the Kunlun fault, which exhibits slip of 2.0 ± 0.4 mm/yr along its eastern segment to
In this study, the moment deficit of the West Qinling fault is recalculated according to the equation, $M_0 = \mu DA$, based on the determined average locking depth and slip deficit (Figure 4), where the shear modulus is assumed to be 30 GPa. This yields an accumulated seismic moment of $1.8 \times 10^{20}$ N-m (or $1.35 \times 10^{20}$ N-m) for the past 400 (or 300) years, corresponding to an earthquake with a moment magnitude of $M_{w7.4}$ (or $M_{w7.35}$), which is smaller than estimated by Wang et al. (2011).

### Strain Transformation and Tectonic Uplift Adjacent to the West Qinling Orogen

Three coexisting end-member models exist to explain the uplift mechanism of the northeastern Tibetan Plateau, where the West Qinling orogen and Liupanshan Mountains are included: 1) strain transformation from horizontal contraction to vertical uplift induced from India-Eurasia oblique convergence (e.g., Tapponnier, 2001; Allen et al., 2017), 2) eastward flow of middle-to-lower crustal materials (Royden, 1997; Royden et al., 2008; Wang et al., 2018), and 3) changes in the balance between stress gradients and body forces, resulting from the removal of lithospheric materials due to asthenospheric flow, and have produced significant topographic relief (England & Houseman, 1989; Molnar et al., 1993; Ye et al., 2017). The latest, dense 3-D geodetic observations provide a new opportunity to reanalyze these models. To identify contemporary crustal deformation features in this region, three vertical velocity and horizontal strain rate profiles are produced, together with the topography along the West Qinling Mountains normal to the West Qinling fault (Figures 2B, 5).

The profiles identify contraction strain rates (red dots in Figure 5) ranging between 0 and $-12.5 \times 10^{-9}$/yr combined with 1–2 mm/yr of uplift (orange dots with gray bars in Figure 5), suggesting transformation of strain from crustal contraction to vertical uplift. Assuming that the volume is conserved, the sum of the three principal strain rates should be zero, and contraction should be equal to, or at least proportional to, uplift (Lease et al., 2012; Ge et al., 2015). Considering a crustal thickness of ~50 km in the northeastern Tibetan Plateau (Guo & Chen, 2017; Ye et al., 2017), the observed contraction can produce maximum uplift of 0.625 mm/yr, consistent with the <1 mm/yr from continuous GPS observations (Su et al., 2018), but smaller than 1–2 mm/yr from our VLM model.

Volumetric conservation requires consistency between the crustal contraction and uplift, however, the opposite relationship is observed in Figure 5, where the largest contraction occurs along with the smallest uplift (at the lowest elevations) and vice versa, especially adjacent to the West Qinling and Liupanshan Mountains, which are also presented in GPS vertical velocities (Su et al., 2018). A possible explanation may come from the different origins of vertical lithospheric stress. To analyze the lithospheric flexure mechanism in the northeastern Tibetan Plateau, Wang et al. (2018) and She et al. (2016) estimated the effective elastic thickness (Te) and loading ratios based on Gravity and GPS hybrid measurements. Their results show that loading ratios of the West Qinling orogen (F1 = 0.19, F2 = 0.42 and F3 = 0.39), with F1, F2 and F3 implying initial...
loading resulting from the Earth’s surface, the interface between the upper and lower crust, and the Moho, suggesting that the initial loading is primarily attributed to the lower crust (i.e., lower crustal materials flow); however, loading ratio of the Liupanshan Mountains \( (F_1 = 0.95; F_2 = 0.05; F_3 = 0) \) indicates that initial loading is primarily attributed to the surface (i.e., strain transformation from crustal contraction to uplift/thickening). Although the existence of middle-to-lower crustal material flow and its contributions to tectonic uplift remain contested (e.g., Lease et al., 2012), seismic tomography identifies complex deep structures beneath the West Qinling orogen and Liupanshan Mountains, i.e., low S-wave velocity underneath the West Qinling orogen at depths of 15–30 km (Yang et al., 2012), low shear-wave velocity in the middle-lower crust but high seismic velocity in the upper crust beneath the West Qinling orogen (Bao et al., 2013), a broad low-velocity zone in the middle-to-lower crust beneath the northeastern Tibetan Plateau (Guo & Chen, 2017; Li S. et al., 2018; Ye et al., 2017), and a complex double Moho structure exists induced from the superposition of the rigid Ordos and the relatively soft northeastern Tibet crust (Li et al., 2017). Therefore, despite quantifying relative contributions from different mechanisms of lithospheric flexure, which still require further investigation (i.e., She et al., 2017; Wang et al., 2018), this study suggests that the strain transformation in the upper crust and complex middle-to-lower crustal structures underneath, control the complex tectonic uplift and geomorphologic/topographic features adjacent to the West Qinling Orogen; i.e., generation of two sets of small-scale active faults, development of several Cenozoic basins (e.g., the Guide, Tongren, Wushan basins; Zheng et al., 2016), and the uplift of the West Qinling Mountains.

Implications for the Outward Growth of the Northeastern Tibetan Plateau

The expansion direction and passage of the northeastern Tibetan Plateau have been contested for decades. In one aspect, some studies suggest that the crustal materials in the northeastern Tibetan Plateau are escaping eastward along the Qinling Mountains and/or beneath the Ordos block (Li S. et al., 2018; Royden et al., 2008; Royden, 1997; Yu & Chen, 2016). Meanwhile, others highlight that the deformation is mainly limited within the plateau and is accommodated by crustal shortening, block rotation, fault movements, and mountain building (Cheng et al., 2015, 2021; Hao et al., 2021; Kirby et al., 2007; Li Y. et al., 2018; Zheng et al., 2016; Zuza and Yin, 2016).

The 3-D crustal deformation model presented in this study indicates that crustal deformation in the northeastern Tibetan plateau is primarily characterized by horizontal contraction, as large as \( 15 \times 10^{-9}/\text{yr} \), as well as vertical uplift/thickening, with the magnitude of 0–3 mm/yr. GPS velocities, with respect to the Ordos block, show significant NNE-ward crustal movement instead of eastward materials escape. These observations support the latter and highlight the importance of strain transformation between horizontal crustal shortening and vertical uplift to accommodate crustal deformation induced from outward growth of the northeastern Tibetan Plateau. Additionally, middle-to-lower crustal material expansion (e.g., middle-to-lower crustal flow) may also have some contributions, especially underneath the West Qinling orogen, which requires further investigations to confirm. Both strain rates and GPS velocities identify a deformation gradient belt at longitudes 105°–106°E, which distinguish significant deformation regions accommodating outward expansion of the northeastern Tibetan Plateau. While we are unable to exclude potential contributions of eastward materials escape, it appears to be inconsequential to our 3-D crustal deformation model (Figures 2A, 3A,B).

CONCLUSION

This study constructed a VLM model based on leveling observations adjacent to the West Qinling orogen, identifying uplift rates of 0–3 mm/yr within this region. Combined with the horizontal strain rate field, this study suggests that strain transformation has played an important role in controlling the tectonic uplift of the West Qinling orogen. Moreover, slip rate and locking coefficients were inverted and the moment deficit of the West Qinling fault was calculated. The West Qinling fault slips slowly at a rate of 1–2 mm/yr and is strongly locked with average locking depths of 6.6, 6.8, and 6.1 km in its western, central, and eastern segments. This equates to a moment magnitude deficit of \( Mw7.4 \). Additionally, results identify a significant deformation transition belt at the longitude of 105°–106°E, which indicates that the deformation of the northeastern Tibetan Plateau is primarily limited to within the plateau, rather than being accommodated by crustal materials that are escaping eastward along the Qinling orogen.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

ZL designed the study and did all the calculations in the paper. ZL wrote the paper, with contributions of FC and ZY. MH and WZ processed the GPS data. SS and FY processed the leveling data.

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