Contemporary crustal tectonic movement in the southern Sichuan-Yunnan block based on dense GPS observation data

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Abstract: We analyzed 360 permanent and campaign GPS data from 1999 to 2017 in the southern Sichuan-Yunnan block, and obtained crustal horizontal deformation in this region. Then, we derived the strain rate using a multi-scale spherical wavelet method. Results reveal a complex pattern of tectonic movement in the southern Sichuan-Yunnan block. Compared to the stable Eurasian plate, the maximum rate of the horizontal deformation in the southern Sichuan-Yunnan block is approximately 22 mm/a. The Xiaojinhe fault shows a significantly lower deformation—a left-lateral strike-slip movement of 9.5 mm/a. The Honghe fault clearly shows a complex segmental deformation from the north to south. The northern Honghe fault shows 4.3 mm/a right strike-slip with 6.7 mm/a extension; the southern Honghe fault shows 1.9 mm/a right strike-slip with 1.9 mm/a extension; the junction zone in the Honghe and Lijiang–Xiaojinhe faults shows an obvious clockwise-rotation deformation. The strain calculation results reveal that the maximum shear-strain rate in this region reaches 70 nstrain/a, concentrated around the Xiaojinhe fault and at the junction of the Honghe and Lijiang–Xiaojinhe faults. We note that most of the earthquakes with magnitudes of 4 and above that occurred in this region were within the high shear strain-rate zones and the strain rate gradient boundary zone, which indicates that the magnitude of strain accumulation is closely related to the seismic activities. Comparison of the fast shear-wave polarization direction of the upper-crust with the upper-mantle anisotropy and the direction of the surface principal compressive strain rate obtained from the inversion of the GPS data reveals that the direction of the surface principal compressive strain is basically consistent with the fast shear-wave polarization direction of the upper crust anisotropy, but different from the polarization direction of the upper mantle. Our results support the hypothesis that the principal elements of the deformation mechanism in the southern Sichuan-Yunnan block are decoupling between the upper and lower crust and ductile flow in the lower crust.

Keywords: GPS data; crustal horizontal deformation; extension; strike slip; strain rate; fast shear-wave polarization

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1. Introduction
The Sichuan-Yunnan rhombic block, located in the southeastern margin of the Tibetan Plateau, is a tectonic unit with the strongest activity among those that extrude eastward from the Tibetan Plateau, and its internal structure shows obvious spatial variations (Deng QD et al., 2003; Xu XW et al., 2003; Chen Y et al., 2013; Wang S et al., 2015). The northeast-oriented Lijiang-Xiaojinhe fault zone divides the block into northern and southern parts, and the southern part is formed by surrounding deep and major fractures such as the Anninghe-Zemuhe, Xiaojiang, and the Honghe fault zones. The interaction between the tectonic movement and fault zones is very complex because of the tectonic movement and escape of materials caused by the uplift of the Tibetan Plateau. With its frequent seismic activity, this region is one of the most active regions with strong earthquakes in China.

Geophysical observations and research have provided large-scale images of tectonic movement and of structures of crustal-upper mantle in the southern Sichuan-Yunnan block (Huang Jl et al., 2002; Wang CY et al., 2003; Yao HJ et al., 2008, 2010). The Global Positioning System (GPS) has been successfully applied to monitor the crustal deformation and tectonic-movement of the seismic zones, and has provided important constraints for the study of crustal deformation patterns in the Tibet Plateau and its surrounding areas (Wang Q et al., 2001; Zhang PZ et al., 2004; Shen ZK et al., 2005; Gan WJ et al., 2007). The GPS velocity fields provided by Gan WJ et al. (2007) and Zhang PZ et al. (2004) relative to the South China block indicate that the Sichuan-Yunnan rhombic block rotates clockwise along the eastern Himalayan tectonic zone, which indicates that the collision of the Indian and Eurasian plates has resulted in the southeastward extrusion of crustal materials from the Tibet Plateau. Studies by Shen ZK et al. (2005) and Pan YJ and Shen WB (2017) used GPS observation data to deduce the horizontal velocity field, fault activity parameters, and strain-rate distribution at the southeastern margin of the Tibet Plateau, and concluded that the viscous-flow effect in the lower crust has played an important role in the crustal deformation of the southeast margin of the Tibetan Plateau.
GPS observations have revealed variations in the crustal-deformation movement inside the Sichuan-Yunnan block (Zhang PZ et al., 2003; Xu XW et al., 2003). The seismic anisotropy can be used to investigate the crustal and mantle deformation in a tectonically active area. Comparison of the GPS-determined deformation to the crustal and upper mantle anisotropy can determine whether the deformations of the lower and upper crust are decoupled, which would be evidence of the existence of a weak layer in the lower crust (Wang CY et al., 2008; Gao Y et al., 2010; Wang S et al., 2015). The direction of the wave-velocity fast axis of seismic anisotropy from the shear-wave splitting analysis is related to fault strike direction and surface strain, which is reflected by the anisotropy of the upper mantle (Sol et al., 2007) and the crust (Gao T et al., 2011). Chen Y et al. (2013) and Wang S et al. (2015) compared the GPS velocity field, tectonic stress field, and crustal anisotropy results obtained from the Sichuan-Yunnan region, and concluded that its upper and lower crusts are coupled. Other studies (Chang LJ et al., 2006; Shi YT et al., 2009, 2012; Lu LY et al., 2014) have indicated that strong azimuthal anisotropy exists on the southeastern margin of the Tibetan Plateau, and obvious spatial variations occur in the direction of the GPS velocities, in the polarization direction of the fast shear-wave splitting, and in the strike direction of the crustal low-velocity layer.

However, the non-uniform station distribution, different observation periods, and different analysis methods in previous research studies provide insufficient resolution. Moreover, studies of tectonic-movement and the dynamic model of the crust in this region have yielded inconsistent results. In particular, the dynamic causes of the clockwise rotational tectonic movement of the Sichuan-Yunnan block and the complex tectonic movement at the block boundary are controversial, and thus have called for further exploration and study. Therefore, in the present study, we collected GPS data since 1999 in the southern Sichuan-Yunnan block with a longer observation period and more intensive distribution, and then obtained current characteristics of the crustal tectonic-movement and strain-rate distributions in stable data of high precision and resolution. We then compared these results with the crustal anisotropy research results to examine the relationship between the current deformation characteristics and the surface and upper crust-mantle movement patterns of the southern Sichuan-Yunnan block.

2. GPS Data and Horizontal Velocity Field
The GPS data used in the study were obtained from the Crustal Movement Observation Network of China (CMONC) and the Yunnan-Sichuan Earthquake Agencies, collected at permanent and campaign stations between January 1999 and December 2017. Data selected for this study were from permanent stations with observation-time spans longer than three years and from campaign stations with observation-time spans longer than four years and from at least three campaigns. Satisfying these conditions were data from 360 GPS observation stations in the southern Sichuan-Yunnan region (21°N–30°N, 97°E–106°E).

The GAMIT/GLOBK (10.61) software was used for data processing, and dual-frequency linear-combination data and relative-positioning mode were adopted. The antenna phase center was calibrated using the ITRF2014 absolute phase center model. In addition, precise satellite orbits were obtained from the IGS (International GNSS Service). The remaining parameters were selected from the latest research results published by MIT (Massachusetts Institute of Technology, http://www-gpsg.mit.edu). The processing period is one day with the prior coordinates constrained to 0.1 m during the calculation to minimize positional deviations. After the baseline computation using the GAMIT software, a whole-network adjustment was performed using GLOBK software where the coordinates and velocities of ITRF2014 core stations were used as the benchmarks. The final coordinates and velocities of all stations were calculated based on the adjusted baseline calculation results. The ITRF2014 reference frame (Altamimi et al., 2016) was realized through the seven-parameter Helmert transformation (which involved the estimation of three azimuthal, three translational, and one scale parameters) of the minimally constrained ITRF2014 core stations. In the time series analysis, a step function was used to correct jumps caused by earthquakes or antenna shifts, and to remove outliers that lay outside two standard deviations during the time-series analysis; the velocity field was obtained using a fitting function (which included linear, annual, and semi-annual terms) within the frame of ITRF2014. Finally, the framework was transformed using the Euler parameter of plate motion to obtain the regional-deformation velocity field relative to the Eurasian frame (Figure 1).

Figure 1. GPS velocity field of the southern part of the Sichuan–Yunnan block relative to the Eurasian plate. The GPS data are obtained from 360 observation stations between 1999 and 2017. The bold white lines represent block boundaries, the solid black lines represent active faults, the blue lines represent velocity profiles across the fault, the red arrows represent velocity; the red rectangle represents the study area. AZ is the Anninghe-Zemuhe fault, XJ is the Xiaojian fault, LX is the Lijiang-Xiaojinhe fault, RR is the Honghe fault, WL is the Wuliangshan fault, LL is the Longling fault, CD is the Sichuan–Yunnan block, HN is the Huanan block, and TP is Tibetan Plateau.

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The solid black line in Figure 1 shows the active faults in the study area, the thick white line represents the boundary of the secondary blocks, and the red arrows represent the horizontal velocity. The GPS velocity distribution shows obvious changes in different areas, which provide evidence of the complexity of the tectonic movement pattern in this region. Relative to the stable Eurasian plate, the maximum deformation of the southern part of the Sichuan-Yunnan block reaches approximately 22 mm/a, whereas the overall trend of the movements shows a clockwise rotation in the southeastward direction. Moreover, the horizontal deformation shows obvious attenuation across the Xiaojiang fault. Similarly, the deformation across the middle-southern section of the Honghe fault also shows attenuation (although not as obvious), where the movement direction is southward. Finally, on the western side of the junction between the northern segment of the Honghe and Lijiang-Xiaojinhe faults, the deformation shows southeastward, whereas the Longling fault area shows an obvious clockwise (eastward) rotational trend.

In order to quantitatively analyze the activity characteristics of the Xiaojiang and Honghe faults, three cross-fault profiles are selected, which are the A-A’ profile with range of 300 km×230 km across the Xiaojiang fault, the B-B’ profile with range of 250 km×200 km across the northern segment of the Honghe fault, and the C-C’ profile with range of 230 km×160 km across the southern segment of the Honghe fault (Figure 1). The velocity in each profile is projected along the vertical and parallel to the fault trend (Figure 2), and its components are \( V_{par} \) and \( V_{per} \) respectively. Then the relative motions \( V_0 \) and coupling depths \( H \) of the faults are estimated from the model of Savage et al. (1999):

\[
V_p = U_0 - V_0 \arctan \left( \frac{V}{H} \right) / \pi. \tag{1}
\]

Here, \( V_p \) is the velocity component parallel to or perpendicular to the fault trend, \( U_0 \) is the overall offset, and \( x \) is the distance from the fault.

Results show that the Xiaojiang fault has relative left-lateral strike-slip of 9.5±1.2 mm/a and tension motion of 0.5 mm/a, and its coupling depth is about 25 km; the northern segment of the Honghe fault has right-lateral strike-slip motion of 4.3±1.5 mm/a and tension motion of 6.7±1.1 mm/a, and its coupling depth is greater than 60 km; the southern segment of Honghe fault has right-lateral strike-slip motion of 1.9±1.0 mm/a and tension motion of 1.9±1.6 mm/a, and its coupling depth is greater than 60 km. These findings indicate that the northern and southern segments of the Honghe fault have different slip rates but with the same slip pattern. The Xiaojiang fault exhibits primarily strike-slip movement; the coupling depth of the Honghe fault is far greater than that of the Xiaojiang fault. However, we need further research to determine whether the coupling depths of the faults are related to crustal thickness or to focal depth. Shen ZK et al. (2005) concluded that the Xiaojiang fault has left-lateral strike-slip motion of 7±2 mm/a, and that the northern section of the Honghe fault has right-lateral strike-slip motion of 2±2 mm/a and extension motion of 2±2 mm/a. However, our results show that the movement patterns of the Honghe and Xiaojiang faults are greater than those obtained by Shen ZK et al. (2005). The differences may be attributed to the different periods of observation data.

Shen ZK et al. (2005) used observation data only from 1998 to 2004; our study is based on data from 1999 to 2017.

3. Strain Calculation Method and Strain Rate Distribution

Strain can reflect the deformation pattern of a medium. There are two ways used to calculate the strain based on horizontal-deformation data: one is to directly calculate discrete strain values according to the deformation data based on the division of triangles or other small units; the other is to derive continuous strain values from the continuous-deformation distribution. In the first method, the observations must be uniformly distributed. The second method combines the continuous basic function and deformation data to establish the continuous-deformation field. In the present study, the strain from continuous-deformation field was established using the multi-scale spherical-wavelet method.

The spherical wavelet method extends wavelet theory from an infinite plane to a limited spherical space; it can be used to establish the GPS crustal movement velocity and strain field. After a wavelet mother function is defined on a unit sphere, a wavelet basis function is obtained through affine transformation (translation and scaling) of the mother function. In addition, any wavelet mother function represented on a plane can be represented on a unit sphere through inverse-mapping transformation; therefore, each mother function has a spherical inverse mapping form (Bogdanova et al., 2005). In the present study, we selected the difference-of-Gaussian function (DOG) to form the spherical DOG wavelet basis function (Bao BC et al., 2009); the surface deformation field is described by its linear combination, and the coefficients are estimated from observation data (Su XN et al., 2016). The DOG wavelet basis function satisfies the following conditions: (1) Rapid attenuation occurs outside the effective support region. (2) The DOG wavelets under different scales have varying degrees of attenuation, namely, the larger the scale factor, the faster the attenuation and the smaller the range of influence. (3) The basic functions of the different scales have different effects on the same observation station. The scaling feature of the wavelet mother function enables the wavelet calculation method to have different spatial resolutions. Ultimately, the spherical-wavelet method allows the processed signal to be decomposed into its different scales, with detailed and smoothed signals at each scale.

The data used in our analysis come from GPS observation stations that are generally not uniformly distributed. In addition, each station is assigned a different weight when the strain-rate field is directly calculated from the GPS velocity field. Therefore, places with a higher concentration of observation points have higher weights, indicating that weight selection largely affects the calculation results (Jiang ZS and Liu JN, 2010). The density of observation data is described by its linear combination, and the coefficients are estimated from observation data. The spherical wavelet method extends wavelet theory from an infinite plane to a limited spherical space; it can be used to establish the GPS crustal movement velocity and strain field. After a wavelet mother function is defined on a unit sphere, a wavelet basis function is obtained through affine transformation (translation and scaling) of the mother function. In addition, any wavelet mother function represented on a plane can be represented on a unit sphere through inverse-mapping transformation; therefore, each mother function has a spherical inverse mapping form (Bogdanova et al., 2005). In the present study, we selected the difference-of-Gaussian function (DOG) to form the spherical DOG wavelet basis function (Bao BC et al., 2009); the surface deformation field is described by its linear combination, and the coefficients are estimated from observation data (Su XN et al., 2016). The DOG wavelet basis function satisfies the following conditions: (1) Rapid attenuation occurs outside the effective support region. (2) The DOG wavelets under different scales have varying degrees of attenuation, namely, the larger the scale factor, the faster the attenuation and the smaller the range of influence. (3) The basic functions of the different scales have different effects on the same observation station. The scaling feature of the wavelet mother function enables the wavelet calculation method to have different spatial resolutions. Ultimately, the spherical-wavelet method allows the processed signal to be decomposed into its different scales, with detailed and smoothed signals at each scale.
GPS stations are contained in the area covered by the graphic unit. When three GPS stations are included, the scale factor corresponding to the smallest graphic unit is the maximum decomposition scale. Meanwhile, the minimum decomposition scale can be determined based on the range of the observation network (Su et al., 2016). The range of the study area in the present study was 900 km × 900 km and had a corresponding minimum decomposition scale of three. The dense distribution of GPS stations in the study area reached approximately 20 km and had a corresponding minimum decomposition scale of eight. During the calculation, a decomposition scale ranging from three to eight was used to obtain the strain related to the various spatial resolutions in different areas.

Spatial distribution of the maximum shear strain, surface strain, rotational strain, and principal strain rates with high resolution...
were obtained by using the multi-scale spherical-wavelet method (Figure 3). The results show that the Anninghe-Zemuhe fault, the Xiaojiang fault, the junction area between the Honghe and Lijiang-Xiaojinhe faults, and the southern segment of the Wuliangshan fault exhibit high shear-strain rates with a maximum value of approximately 70 nstrain/a. They indicate that there are relative motions of faults. The shear strain in the middle segment of the Honghe fault was found to be practically zero, which means that the middle segment of the Honghe fault has no relative motion, perhaps indicating that the fault activity in this region is in a locked state (Figure 3a). The rate and direction of the principal strain indicated the shortening or extension, which allows characterization of the fault activity. The overall tendency of the Xiaojiang fault is strike slip. The junction between the northern segment of the Honghe and Lijiang-Xiaojinhe faults is dominated by extension (with partial strike slip). The Longling fault exhibits a strike slip. Parts of the Wuliangshan area show extension, and the rest display a strike slip. The relative movement of the middle-southern segment of the Honghe fault is minimal, which makes it impossible to determine the prevailing fault activity pattern in this area. The surface strain rate (Figure 3b) indicates the expansion (positive) and compression (negative) rates. The boundary area between the Lijiang-Xiaojinhe and Honghe faults is expanding. The eastern side of the Wuliangshan fault is expanding; its west-

**Figure 3.** Strain rate distribution obtained from the GPS horizontal velocity in southern Sichuan-Yunnan block. (a) Distribution of shear- and principal-strain rates (black arrows indicate extension and compression); (b) Surface-strain rate distribution (positive values indicate expansion; negative values indicate compression); (c) Rotational-strain rate distribution (positive values indicate clockwise rotation; negative values indicate counterclockwise rotation).
ern side is compressing. The Yunnan area in the south of the Lijiang–Xiaojinhe fault is entirely compressing, which is consistent with the thickening of crust in this region as revealed by study of deep structures (Zhang EH et al., 2013). The rotational strain rate indicates a rotational-deformation trend (Figure 3c). The rotational-strain rate of the Xiaojinhe fault was negative with a counterclockwise deformation (eastward). The rotational strain rate of the Lijiang–Xiaojinhe and Honghe faults is close to zero; the rotational deformation within the southern Sichuan–Yunnan block and that in the western side of the Honghe fault is positive (rotating clockwise and westward).

In summary, the deformation patterns of the faulted structures in the southern Sichuan–Yunnan block area are very complex. In particular, the Honghe fault shows an obvious segmental movement pattern, whereas the two sides of its middle-southern section show minimal relative movement. To provide detailed deformation characteristics of the fault activity, we need high-resolution and high-precision data to determine the distribution of the deformation velocity field. However, the currently available station density and observation periods of GPS observations in this region cannot satisfy such research requirements. Therefore, the observation density needs to be increased to adequately quantify the fault activity.

4. Analysis

The tectonic activity and escape of materials due to the uplift of the Tibetan Plateau cause complex tectonic activity and interactions among fault zones in the southern Sichuan–Yunnan block, which results in numerous seismic activities. The deformation velocity field and strain rate distribution obtained from the GPS observation data from 360 stations in the study area clearly demonstrate the complex tectonic activity and fault movement in this region. By analyzing the spatial distribution of strain rate and earthquakes with magnitude 4 or more occurring in this area since 1966 (Figure 4), we find that earthquakes have usually occurred in areas of high shear strain rate and at the boundary of the strain rate gradient. This finding shows that the distribution of shear strain rate and its gradient is closely related to the seismicity; i.e., areas with high shear strain rate or strain rate gradients are seismically active. Therefore, the regional shear strain rate distribution obtained from GPS observation data can be used to identify earthquake-risk zones.

We should note that no obvious relative movement occurred between the two sides of the middle-southern segment of the Honghe fault near 24°N. Moreover, the strain accumulation of these areas is minimal, which indicates that fault locking has occurred in this area or that no slip has occurred throughout the depth range in the middle section. Because this region is a seismic “blank area,” if fault locking is indeed present here, then the region is a high-risk zone for earthquakes. Therefore, we believe that further research and detailed observations are required in this area. Although the resolution, magnitude, and direction of the present study results are slightly different from those reported by Pan YJ and Shen WB (2017), such differences could reflect variations in the observation times, numbers of GPS stations, and methods of strain calculation employed. The results of Pan YJ and Shen WB (2017) were smoother, which made them more suitable for explaining large-scale regional tectonic movement. On the other hand, the high-resolution results of the present study reflect more detailed variations and are thus more conducive to explaining fault activity and tectonic movement in small regions.

Many studies have shown that an understanding of the seismic

Figure 4. Comparison between the shear-strain rate (a) and strain rate gradient (b) with seismic activity distributions in the southern Sichuan–Yunnan block. Shear-strain results obtained from the inversion of GPS observations collected from 1999 to 2017 (color isogram). Data of magnitude 4 and above earthquakes from January 1966 to June 2018 based on the data obtained from the China Seismic Network Catalog (circles).
anisotropy of a region can provide important information about the deformation of the crust and upper mantle beneath a tectonically active zone. However, non-uniform crust thickness and shear-wave velocity lead to complex deformation patterns. Therefore, by comparing and analyzing the results of the GPS deformation and crustal anisotropy calculations, both deep and shallow crustal tectonic activities can be studied. In the present work, to further improve basic understanding of the complex crustal tectonic movement patterns of the southern Sichuan-Yunnan block, the results of studies (Shi YJ et al., 2012; Chang LJ et al., 2015; Tai LX et al., 2015) in the fast shear-wave direction of the upper crust and upper mantle anisotropy were compared with the principal compressive strain directions estimated using GPS seismic station data in this region (Figure 5). From the nature of the data, the upper mantle anisotropy here is actually the crust-upper mantle anisotropy including the crust. Researchers believe that the thinner crust anisotropy is very weak, and the anisotropy is mainly from the upper mantle.

Although the direction of the GPS principal compressive strain is found to be basically consistent with the fast shear wave polarization direction of the upper crust anisotropy in most seismic stations, some discrepancies are present in several adjacent stations, which all show similar characteristics when such discrepancies occur; this result can be interpreted as the effect of the complexity of underground structures and the influence of faults near the stations. This condition means that in most areas in the southern Sichuan-Yunnan block, the tectonic movement and deformation of the surface and upper crusts were consistent. On the other hand, the direction of the GPS principal compressive strain rate and the direction of fast shear-wave polarization of the upper mantle anisotropy are inconsistent in most areas, which indicates that the upper crust and upper mantle are undergoing different deformation patterns. This result also suggests the occurrence of crust-mantle decoupling. However, in the fast shear wave polarization direction "transition zone" (close to 26°N) (Lev et al., 2006; Wang CY et al., 2008; Shi YT et al., 2012; Huang ZC et al., 2015a, b; Chang LJ et al., 2015), the direction of the GPS principal compressive strain is consistent with the direction of the fast shear-wave polarization of the upper mantle anisotropy, indicating that no crust–mantle decoupling has occurred in this area.

Numerous studies have directly compared GPS velocity field and crustal anisotropy results in the Sichuan-Yunnan region to investigate whether crust-mantle decoupling has occurred in this region. However, GPS velocity is a deformation vector in a fixed coordinate frame. Therefore, because the velocity-vector distribution changes when a different reference frame is selected, it is difficult to assess correctly whether crust-mantle decoupling has indeed occurred based on a direct comparison between the anisotropic results and GPS velocity. However, the strain obtained from inversion of a GPS velocity field is independent of the selected reference frame, which means that velocity fields based on different reference frames have identical strains. Therefore, comparing the principal compressive strain direction obtained from GPS data with shear-wave anisotropy results is more conducive to an improved understanding of the crust-mantle and upper-lower crust decoupling.

5. Discussion and Conclusions
In the present study, GPS observations collected between 1999 and 2017 from 360 stations were used to obtain the current horizontal velocity and strain rate distribution in the southern

![Figure 5](image-url)
Sichuan-Yunnan block region, and to ultimately analyze the tectonic-movement characteristics in this region. In addition, deep and shallow tectonic-movement patterns were discussed based on comparison between upper crust anisotropy and upper mantle anisotropy (it is the crust-upper mantle that contains the crust). The main findings of this study are presented as follows:

(1) The GPS velocity field and strain-rate distribution significantly vary in different areas and fault zones, which clearly illustrates the complex regional tectonic movement in the southern Sichuan-Yunnan block region. The Xiaojiang fault is characterized by an overall left-lateral strike slip, high strain accumulation, and high seismic activity. The northern, middle, and southern segments of the Honghe fault display significantly different tectonic activities, which demonstrate a segmental movement pattern. The northern and southern segment is a high-strain rate accumulation zone dominated by extension and right-lateral strike slip; the relative movement rate and locking state of the middle segment remain unclear, due to the sparse distribution of observation data; the junction between the northern part of the Honghe and Lijiang-Xiaojinhe faults is dominated by extension with partial strike slip, whereas the Longling fault and southern segment of the Wuliangshan fault show a strike slip movement. All these regions show high strain rate accumulation. Areas exhibiting high shear strain rate and at the boundary of strain rate gradients are earthquake-prone areas, characterized by high seismic activities, which indicate that the magnitude of the strain accumulation is related to seismic activity.

(2) The fast shear-wave polarization direction of the upper crust anisotropy is consistent with the direction of the GPS principal compressive strain in the southern Sichuan-Yunnan block region, indicating that the surface deformation and tectonic deformation of the upper crust in this region are consistent. However, significant discrepancies exist between the fast shear wave polarization of the upper mantle anisotropy and the direction of GPS principal compressive strain, which suggests that in this region the upper and lower crusts and the upper mantle may have inconsistent deformation patterns. Shi YT et al. (2012) report that the time delay of S-wave splitting of upper mantle anisotropy is mainly between 1.0 and 1.4 s, and the anisotropic layer is mainly in the lithosphere with an average thickness of about 130 km. Upper crustal anisotropy mainly reflects brittle crust over 20 km. Combined with studies of the lower crust velocity structure, which show that the lower crust of the southern Sichuan-Yunnan block has a low velocity, the difference between upper crust anisotropy and lithospheric (crust-upper mantle) anisotropy can be reasonably explained. In view of the above, the results of the present study also support the view that the lower crust in the southern Sichuan-Yunnan block is characterized by a ductile flow.

(3) The distribution of observation stations is non-uniform, and the data precision is limited. Therefore, accurately interpreting the complex crustal tectonic movement in some areas such as in the transition zone of the fast shear-wave polarization of the upper mantle anisotropy (near the southern side of the Lijiang-Xiaojinhe fault) and in the Honghe fault region is not possible. A denser distribution of observation stations that can provide high-resolution high-precision observation data is required for more accurate understanding of the complex deep-shallow structure and to compile a more accurate tectonic movement pattern of the southern Sichuan-Yunnan region. Finally, we suggest that the multi scale spherical wavelet method may be advantageous for extracting high-resolution deformation information in regions that have a complex deformation distribution and high observation density.

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