

Article

Deformation Distribution Characteristics and Seismic Hazard of the Xianshuihe Fault Zone Based on GNSS and InSAR Data

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Abstract: The spatial distribution characteristics and slip rate in the Xianshuihe Fault Zone (XSHFZ) are still subject to controversy, and the segments where creeping movement occurs within the fault remain unclear. In this paper, the three-dimensional deformation field of the XSHFZ and its neighboring areas is obtained by integrating InSAR and GNSS data. Subsequently, based on the three-dimensional deformation field, an elastic dislocation model is employed to analyze the slip rate, locking state, and creeping movement within the XSHFZ. The results show that the XSHFZ is a typical sinistral strike-slip fault with compressional characteristics. The slip rate of the XSHFZ ranges from 9.3 to 14.3 mm/yr. The average strike-slip rate of the Qianning and Kangding segments surpasses that of the eastern and western segments, while the Moxi segment exhibits the lowest slip rate. The locking depth of the XSHFZ is estimated to be between 13 and 26 km, with shallow creep movement predominantly concentrated in three segments: Daofu, Qianning, and Kangding, where the shallow creep rate ranges from 1.5 to 4.9 mm/yr. The XSHFZ is known for its short recurrence period of strong earthquakes and frequent seismic activities. A quantitative study of fault slip rates, locking depth, and creeping movement provides essential support for analyzing its seismic hazards. The seismic hazard of each segment of the Xianshuihe Fault Zone (XSHFZ) was analyzed based on the principle of seismic moment balance. The areas with high seismic hazards in the Xianshuihe Fault Zone correspond to the locations of seismic gaps along the fault. Specifically, the Qianning segment and the Yalahe and Selaha faults within the Kangding segment are associated with seismic gaps and are at risk of experiencing earthquakes with magnitudes of 6.9, 6.9, and 6.6, respectively. The results highlight the importance of continuous monitoring and preparedness measures to mitigate the seismic risks present in the XSHFZ.

Keywords: the Xianshuihe fault zone; three-dimensional deformation field; fault strike-slip rate; locking depth; seismic hazard



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1. Introduction

Located on the southeastern margin of the Tibetan Plateau, in the south-central part of the north-south seismic belt, and in the northern part of the eastern boundary of the Sichuan-Yunnan block, the Xianshuihe Fault Zone (XSHFZ) is known for its high slip rate and frequent occurrence of strong earthquakes (Figure 1). The XSHFZ is a Holocene left-lateral strike-slip fault zone that plays an important role in studying tectonic deformation processes and dynamic mechanisms in the eastern Tibetan Plateau. There is still some controversy about the slip rate of the XSHFZ, as the slip rates reported in different studies vary widely. Geologically, the slip rate of the northwestern segment of the XSHFZ since the Late Quaternary has been estimated at 7–20 mm/yr based on various papers utilizing

geomorphologic features such as terraces and gullies along with chronological data [1–10]. A relatively high slip rate as high as 30 mm/yr was reported by Wang et al. [11]. The XSHFZ is segmented into three secondary faults—the Yalahe, Selaha, and Zheduotang faults—spanning from the south of the Huiyuan Temple basin to the south of Kangding. Slip rates in the northwestern segment of the XSHFZ are not evenly distributed across these three faults [4,12]. Since the Late Quaternary, the horizontal slip rate of the Yalahe fault based on geologic methods is 1–3 mm/yr [4,12], the slip rate of the Selaha fault is 5–10 mm/yr [5,7,8], and the slip rate of the Zheduotang fault is 3.6–6 mm/yr [8], while that of the segment south of the Kangding ranges from 5 to 9.1 ± 2 mm/yr [1,2,4]. With the development of space-based Earth observation technology, the Global Navigation Satellite System (GNSS) and Interferometric Synthetic Aperture Radar (InSAR) techniques have been widely used to obtain the slip rate of the fault zone. Most of the slip rates given by GNSS and InSAR for the XSHFZ are 7–15 mm/yr [13–25].

Creeping movement on faults induces alterations in the stress state, subsequently impacting earthquake generation. The XSHFZ stands out as one of China's few fault zones exhibiting creep characteristics. Since Allen et al. [1] first proposed the existence of shallow creep in the Luhuo–Daofu segment of the XSHFZ, there have been several studies on the creep characteristics of the fault zone [16,26–31]. Wang et al. [26] obtained the dynamic evolution trajectory of the high-precision deformation field across the XSHFZ by utilizing two pairs of GPS continuous observation stations. This method reflected the unsteady deformation characteristics of the Daofu segment within the XSHFZ. Du et al. [27] analyzed the near-field deformation and slip changes of the Luhuo segment following the magnitude 7.6 earthquake in 1973. They discovered that the fault's slip rate was 10.27 mm/yr in the initial 5 years post-earthquake; however, this rate has progressively declined to 0.66–2.52 mm/yr since 1979. Zhang et al. [28] investigated the surface creep and fault slip rate of the northwestern segment of the XSHFZ by employing a short baseline and short-level measurements across the fault over recent decades. Their study revealed that the slip rate of the fault zone displays spatial and temporal variability. The high-spatial-resolution velocity field provided by InSAR can offer sufficient data support for studying the creep characteristics of the XSHFZ. Sun et al. [29] and Chen et al. [31] investigated the creep characteristics of the northwestern segment of the XSHFZ utilizing InSAR data. In contrast, Qiao and Zhou [30] analyzed the creep characteristics of the entire XSHFZ based on InSAR data. It is crucial to delineate the creep segments and quantify the magnitude of the creep slip rate in the XSHFZ to comprehend regional seismic hazards. Previous studies are mainly based on single sources to analyze the creep characteristics of the XSHFZ, and there are also studies fusing GNSS data, e.g., Wang et al. [13] and Sun et al. [29], but these studies only focused on the northwestern segment of the fault zone. This paper aims to utilize the three-dimensional deformation field obtained by integrating InSAR and GNSS data to assess the comprehensive characteristics of creeping movement along the XSHFZ.

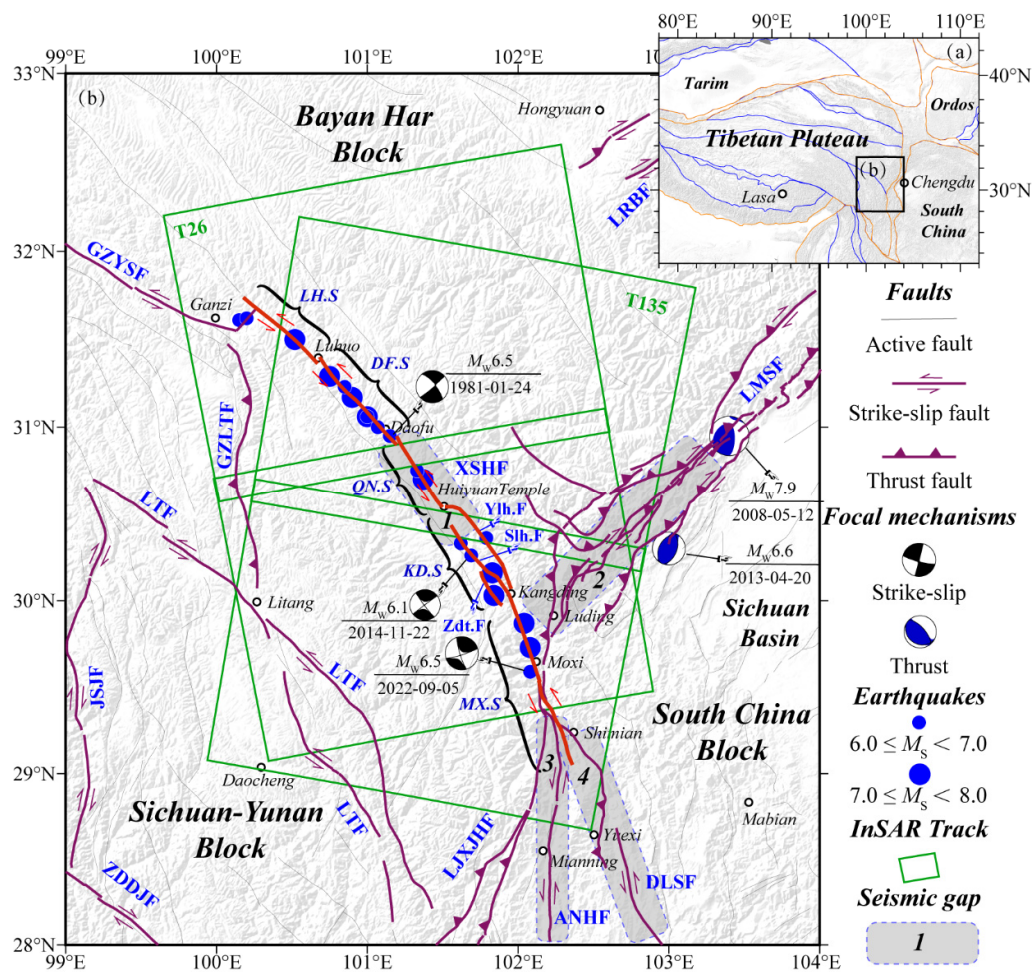


Figure 1. Seismotectonic background of the XSHFZ. (a) Index location map of the study area. The primary and secondary active landmass boundaries on the map are based on Zhang et al. [32]. (b) Segmentation and seismic activity characteristics of the XSHFZ. The fault zones depicted on the map are sourced from Xu et al. [33]. Fault names: XSHF = Xianshuihe fault; LMSF = Longmenshan fault; LRBF = Longriba fault; GZYSF = Ganzi–Yushu fault; ANHF = Anninghe fault; DLSF = Daliangshan fault; LJXJHF = Lijiang–Xiaojinhe fault; LTF = Litang fault; ZDDJF = Zhongdian–Daju fault; JSJF = Jinshajiang fault. The gray areas with numerical labels enclosed by dashed blue lines represent the seismic gaps in the XSHFZ and Longmenshan fault zone. LH.S, DF.S, QN.S, KD.S, and MX.S represent the Luohuo, Daofu, Qianning, Kangding, and Moxi segments of the XSHFZ, respectively. The Kangding segment is divided into three sub-secondary faults: Yalahe fault (Ylh.F), Selaha fault (Slh.F), and Zheduotang fault (Zdt.F). The green border signifies the trajectory of the InSAR data, where T26 denotes the ascending track and T135 signifies the descending track.

The XSHFZ experiences frequent and intense seismic activity, with previous studies indicating that historical earthquake records of magnitude 7.0 or higher since 1700 and magnitude 6.0 or higher since 1900 are complete for the XSHFZ region [34–38]. Within the XSHFZ, there have been nine significant earthquakes with a magnitude of $M_S \geq 7.0$ in the last 320 years since 1700. Additionally, 10 earthquakes with magnitudes larger than 6.0 have occurred in the XSHFZ since 1900 (Figure 1). The most recent earthquake of magnitude 6 or higher was the 6.8-magnitude Luding earthquake on 5 September 2022. In conjunction with seismic activity, several researchers have conducted studies around strong seismic activity behavior and seismic hazard. Wen [10,39,40] and Wen et al. [41] conducted thorough and systematic studies utilizing historically significant earthquakes, seismic activity parameters, and time-dependent probabilistic approaches for XSHFZ. Ran and He [42] established a rupture model based on the geologic parameters of the northwest segment of the XSHFZ,

and used the seismic moment method to assess the future seismic recurrence period of the northwest segment as 100–150 years. Yi et al. [43] used b-value scanning to discuss the danger areas for future strong earthquakes in the south–central segment of the XSHFZ and concluded that there is a danger of strong earthquakes in the segment between Daofu and Qianning. Papadimitriou et al. [44], Xu et al. [45], and Shao et al. [46], on the other hand, discussed the future risk of strong earthquakes in the XSHFZ through the relationship between the Coulomb stress changes and strong earthquakes. Most of the aforementioned studies have been conducted on specific segments of the fault zone, with the Coulomb stress analysis emphasizing the examination of triggering mechanisms between significant earthquakes. The XSHFZ traverses several cities such as Luhuo, Daofu, and Kangding from northwest to southeast. Given the large population residing along the fault zone, conducting a comprehensive study on the strong seismic hazard background of the XSHFZ holds great practical significance. The earthquake cycle is a process of energy accumulation and release, and it is necessary to systematically study the risk of strong earthquakes in the whole fault zone from the perspective of the balance between the accumulation and release of seismic moments.

In this paper, the high-precision three-dimensional (3D) deformation field is obtained by integrating InSAR and GNSS data. Then, based on the results of the 3D deformation field, the spatial changes in the slip rate and locking characteristics of the XSHFZ are analyzed, and the creeping movement along the XSHFZ is further analyzed. Finally, the potential strong earthquake risk of each segment of the XSHFZ is analyzed according to the principle of seismic moment equilibrium.

2. Active Tectonic and Seismic Background

The interactions among the Indian, Pacific, and Philippine plates with the Eurasian plate, along with geodynamic interactions within the Eurasian plate, have led to diverse forms of active tectonics in China. These interactions control the spatial distribution of strong earthquakes in the region [47–50]. The present tectonic characteristics of the Tibetan Plateau are outcomes of the collision between the Indian and Eurasian plates approximately 50–60 million years ago [51,52]. Researchers such as Armijo et al. [52], Fielding [53], and Tapponnier et al. [49] have studied this phenomenon, highlighting important aspects like the emergence of extensive Late Quaternary active faults. These faults' kinematic properties and deformations play an important role in governing the convergence between the Eurasian Plate and the Indian Plate, along with the uplift of the Tibetan Plateau. The XSHFZ is a large left-lateral strike-slip fault zone on the eastern margin of the Tibetan Plateau [32], with a strike of about N40°W and a slight arcuate bend projecting to the northeast (Figure 1). The XSHFZ originates in the northwest from the northeast of Ganzi and stretches southeastward through Luhuo, Daofu, Huiyuan Temple, Kangding, and Moxi to the vicinity of the Gongyi Sea, with a total length of approximately 400 km [33]. Concerning the segmentation of the XSHFZ, various studies have presented divergent outcomes. The prevailing division categorizes the XSHFZ into three segments: the northwest segment, the middle segment, and the southeast segment, with Huiyuan Temple and Kangding serving as delineating boundaries for each segment, respectively [9,54]. To the northwest of the Huiyuan Temple, the geometric structure of the XSHFZ is relatively straightforward, comprising the Luhuo segment (S1), the Daofu segment (S2), and the Qianning segment (S3) from northwest to southeast, exhibiting a left-oriented arrangement pattern. South of Huiyuan Temple, the Kangding segment (S4) in the central region of the XSHFZ is further divided into three subsidiary faults: the Yalahe fault, the Selaha fault, and the Zheduotang fault. To the southeast is the Moxi segment (S5) of the XSHFZ (Figure 1), with the fault trace once again extending as a single primary fault, reaching toward the vicinity of the Gongyi Sea [9,46].

The Luhuo segment of the XSHFZ has an overall length of approximately 62 km, featuring a general strike direction of N315°. It is noteworthy that the 1973 M_s 7.6 earthquake transpired within this segment (Figure 2). The Daofu segment spans approximately

85 km in length, exhibiting a predominant strike direction ranging from N310° to N325°. The Daofu segment stands out as the most seismically active area within the XSHFZ, witnessing seven earthquakes of magnitude 6 or greater, among which three earthquakes of magnitude 7 or higher occurred. These notable events include the 1816 M_S 7.5 earthquake, the 1904 M_S 7 earthquake, and the 1923 M_S 7.3 earthquake (Figure 2). The Qianning segment spans roughly 54 km in length, and it experienced a magnitude 7 earthquake in 1893. The main basis for the division of the three secondary faults north of Huiyuan Temple in the XSHFZ is the existence of pull-apart basins of a certain scale between adjacent segments, the Xialatuo Basin and Daofu Basin. Simultaneously, these three segments exhibit structural similarities, with the two adjacent fractures being arranged in a left-stepping pattern. The lengths of the three secondary faults in the middle segment of the XSHFZ from north to south are approximately 70 km, 60 km, and 26 km, respectively. Notably, the M_S 7 earthquake of 1725 and the M_S 7.5 earthquake of 1955 transpired on the Selaha River fault and Zheduotang fault, respectively. The total length of the Moxi segment is approximately 120 km, with historical earthquakes primarily concentrated in its central and northern regions. Notably, two earthquakes of magnitude 7 or higher were recorded in 1327 (M_S 7.5) and 1786 (M_S 7.7).

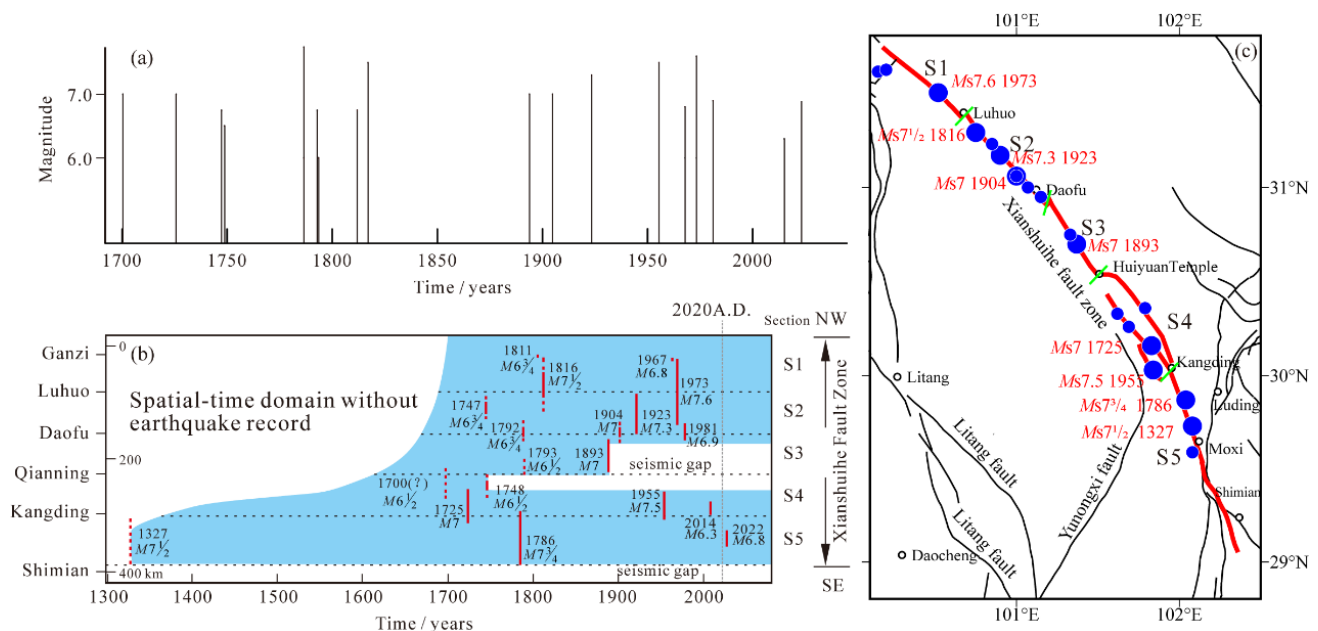


Figure 2. The temporal and spatial distribution characteristics of earthquakes on the XSHFZ (modified by Wen et al. [41]; Shao et al. [46]; and Li et al. [55]). (a) Seismic moment–magnitude (M–T) graph; (b) rupture distribution characteristics of earthquakes with a magnitude of 6 or above [41]; (c) fault segmentation [9,54] and the spatial distribution characteristics of earthquakes from Wen et al. [41] and CENC (<https://www.cenc.ac.cn>).

Seismic gaps are segments within extensive active rupture zones that have not experienced significant earthquakes for a prolonged period. These gaps may accumulate more stress and strain compared to neighboring segments that have also been seismically quiet for an extended time. Consequently, these zones could present an increased risk for future large earthquakes [56]. Wen et al. [41] synthesized the distribution characteristics of historical and modern earthquakes, aftershocks, etc., and obtained information on the distribution of rupture areas of these earthquakes on the XSHFZ, based on which the seismic gaps in the central and southern segments of the XSHFZ were determined (Figure 2). The seismic gap in the middle segment of the XSHFZ is situated between Tagong in Kangding and Songlinkou in Daofu, with its central point positioned between Bamei and Kangding Airport in Daofu County. This seismic gap spans approximately 100 km along the XSHFZ. The northeastern and southeastern boundaries of this seismic gap were affected by the

1981 Daofu earthquake with a magnitude of 6.9 and the 1955 Kangding earthquake with a magnitude of 7.5, respectively. The most recent seismic events within the seismic gap were the 1748 earthquake with a magnitude of at least 6.5 and the 1893 earthquake with a magnitude of 7 [41].

3. Data and Methods

3.1. GNSS, InSAR, and Leveling Data

High-precision deformation fields are essential for accurately determining fault slip distribution and quantifying the slip rate. In this study, high-quality InSAR, GNSS, and leveling data were used to obtain a high-precision three-dimensional deformation field encompassing the XSHFZ. The InSAR velocity maps in Figure 3 were compiled by processing Sentinel-1 data from ascending and descending tracks spanning the period from 2014 to 2021 [22]. The GNSS velocity field results, relative to the Eurasian framework, are sourced from Wang and Shen [21], spanning from 1991 to 2016. We also employ regional precise leveling data to validate the vertical velocity resulting from the fusion of InSAR and GNSS velocities. The leveling data's observational period spans from 1970 to 2017 [57]. For the detailed processing of the three types of data, refer to the following references [21,22,57].

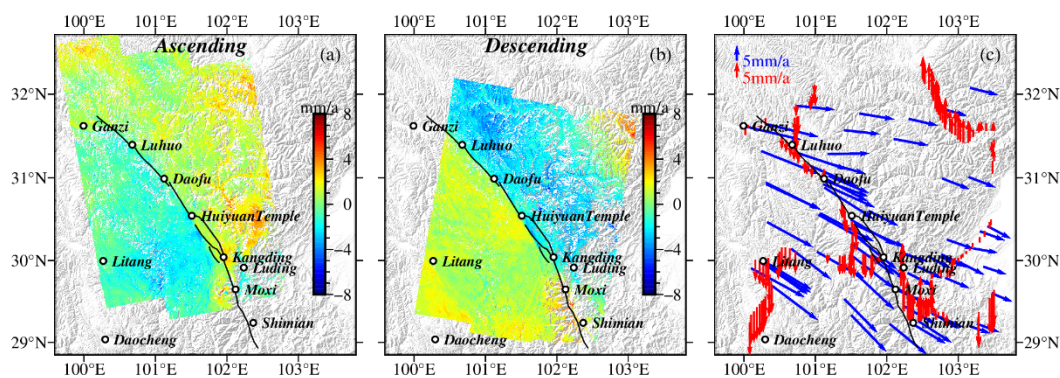


Figure 3. Mean line-of-sight (LOS) velocities derived using the Small Baseline Subset (SBAS) technique for (a) the T26 ascending track and (b) the T135 descending track [22]. (c) The GNSS velocities with respect to the Eurasia plate during the period of 1991–2016 [21] and the vertical velocities were derived from the leveling data using a Helmert joint adjustment method [57].

3.2. Calculation of Three-Dimensional Deformation Field

The least-squares variance component estimation (LS-VCE) method [58,59] was utilized to calculate the high-precision 3D field (Figure 4) by combining the InSAR and GNSS velocity fields. First, the GNSS horizontal deformation rate field is interpolated based on the InSAR grid points. Then, by combining the ascending and descending InSAR data with the east–west and north–south GNSS deformation components, the 3D deformation components are calculated. Specific calculation formulas can be found in the work by Guo et al. [60].

3.3. Calculation of Fault Slip Rate and Locking Depth

Slip rate and locking depth are important parameters for quantitatively studying the characteristics of fault movement and deformation, as well as the regional seismic hazard. During interseismic periods, fault zones are seismically locked above a certain depth. Below this locking depth, the fault zone is characterized by continuous sliding motion. The two-dimensional elastic dislocation model method [61–63] can effectively connect the velocity of crustal deformation during the interseismic period with the long-term slip rate of the fault and is widely used for quantitative analysis of the slip rate and locking depth of the fault. Based on the elastic dislocation model [61–63], the Bayesian Monte Carlo inversion method is used to calculate the slip rate and locking depth of 20 sections, each about 200 km long and 10 km wide, on the XSHFZ (the fault distribution is shown in Figure 1) to obtain

the spatial distribution characteristics of the slip rate and locking depth of the XSHFZ. In this method, the strike-slip component parallel to the fault is fitted using formula (1), while the slip rate perpendicular to the fault and the relative vertical slip rate on both sides of the fault are obtained by taking the average of the slip rates on both sides of the fault and then differentiating [60,64,65].

$$V_{para} = \frac{s}{\pi} \tan^{-1}\left(\frac{x}{d}\right) + a \quad (1)$$

where V_{para} is the rate component of the parallel fault of the surface site, a is the migration constant, s is the long-term strike-slip rate of the fault zone, d is the locking depth of the fault, and x is the distance from the site to the fault.

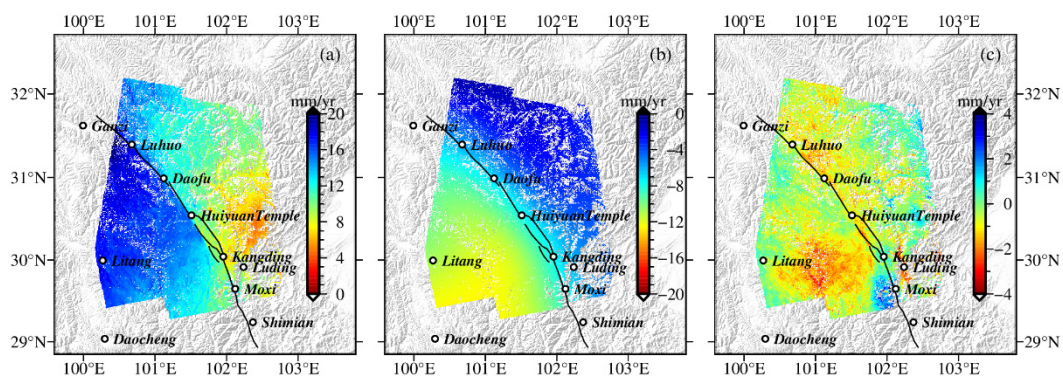


Figure 4. Three-dimensional displacement velocity maps estimated by integrating the GNSS and InSAR data. (a) East–west component. (b) North–south component. (c) Up–down component.

4. Results

4.1. Distribution Features of Fault Slip Rate and Locking Depth

The strike-slip velocity, compression velocity, and vertical relative deformation rate on both sides of different segments of the Xianshuihe fault (Figure 5) show significant spatial variation. The data (Figure 5a) indicate that the left-lateral strike-slip rate of the Xianshuihe fault is 9.3–14.3 mm/yr. The maximum slip rate is at the southeast end of the Kangding segment of the XSHFZ (14.3 mm/yr), and the minimum slip rate is at the southeast end of the Moxi segment (9.3 mm/yr). The slip rate generally shows a characteristic of being higher in the middle and lower at both ends. The tectonic loading rate of the XSHFZ inverted in this paper is largely consistent with the slip rate (7–15 mm/yr) reported in existing geodetic results [13–25]; the locking depth primarily ranges between 13 and 26 km, which is in good agreement with the findings of He et al. [66]. The probability density distribution of the kinematic parameter estimation is provided in Supplementary Figure S1, demonstrating the accuracy of the parameter estimation. Perpendicular to the fault direction, a significant compression feature is observed, with a fault compression velocity of 0–3.6 mm/yr. The relative vertical rate on both sides of the fault shows a significant segmented characteristic, with the overall vertical relative deformation rate on both sides of the fault being less than 2 mm/yr. Compared with existing research results [12,22], this study more clearly illustrates the spatial distribution characteristics of the three-dimensional movement rate of the XSHFZ.

4.2. The Deformation Distribution Characteristics in the Kangding Segment

The Kangding segment of the XSHFZ comprises three branch faults from north to south: the Yalahe fault, the Selaha fault, and the Zheduotang fault. Understanding the distribution of deformation among these three branch faults is crucial for comprehending the movement characteristics of the XSHFZ. The results indicate that the slip rate of the Selaha fault segment is 8.9 ± 0.1 mm/yr with a locking depth of 14.5 ± 0.2 km, while the slip rate of the Yalahe fault is 4.6 ± 0.1 mm/yr with a locking depth of 21.8 ± 0.5 km (Figure 6).

These findings align well with previous studies [1,4,8,9,67] which reported slip rates ranging from 9.6 to 9.9 mm/yr for the Selaha fault and 0.6–3 mm/yr for the Yalahe fault. Figure 7 shows that employing an elastic dislocation model to invert the Zheduotang fault yields a slip rate of approximately 5.5 ± 0.3 mm/yr, consistent with previous studies [7–9,67] reporting a slip rate between 3.4 and 4.8 mm/yr. Furthermore, the locking depth of the Zheduotang fault is estimated at 14.2 ± 2.3 km. The analysis conducted herein, utilizing high-resolution three-dimensional deformation fields, establishes a reliable foundation for further investigation into the seismic risk associated with different fault segments.

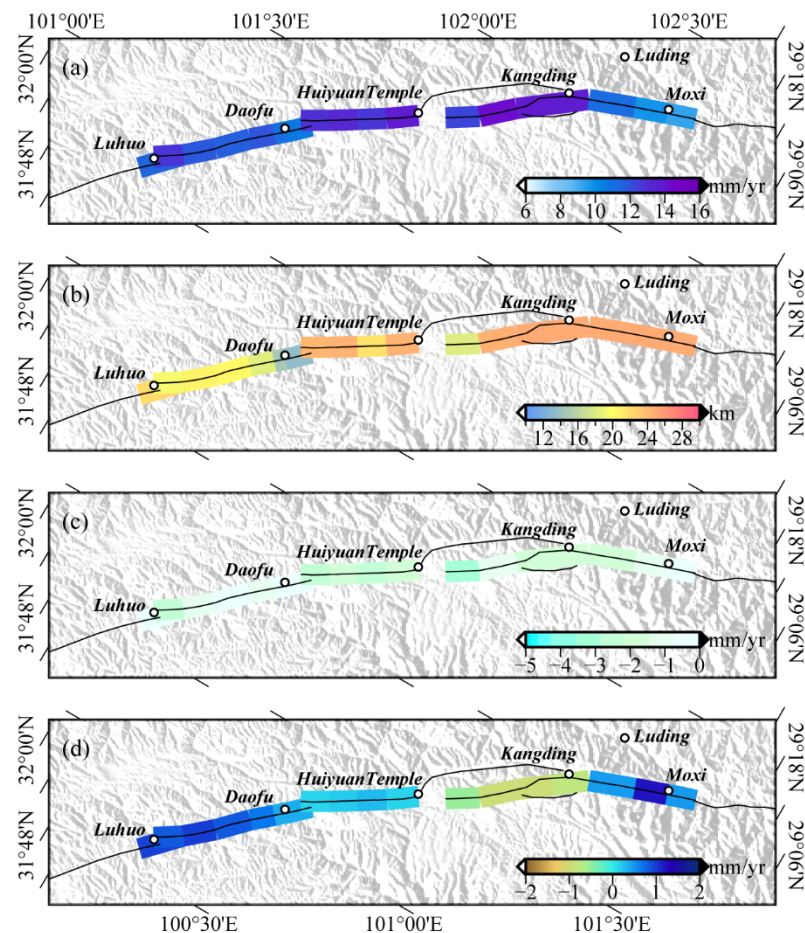


Figure 5. Three-dimensional kinematic deformation characteristics of the XSHFZ: (a) fault-parallel strike-slip rate; (b) locking depth; (c) fault-normal compression rate; and (d) vertical slip rate.

4.3. Creep Distribution Features of the Xianshuihe Fault Zone

To better identify the spatial location of the creeping movement on the XSHFZ and illustrate its variations in creep rate, a total of 20 cross-fault profiles were utilized. Employing the elastic dislocation model, the Bayes Monte Carlo method was utilized to invert the slip rate and locking depth of the fault, thereby precisely locating and quantifying the slip rate of the creep section on the XSHFZ. The creep rates and locking depth of these sections are depicted in Figure 8. The calculated results reveal that the XSHFZ exhibits a range of creep rates from 1.5 to 4.9 mm/yr, with an average value of 3.5 mm/yr. Moreover, the results reveal significant shallow creep characteristics (locking depth < 3 km) for P2–P5 sections, validating a shallow slip extent along approximately 120 km lengthwise along strike on the XSHFZ within specific coordinates ranging from 100.76 to 101.86° longitude. Figure S2 provides the probability density distribution for kinematic parameter estimation, validating its accuracy.

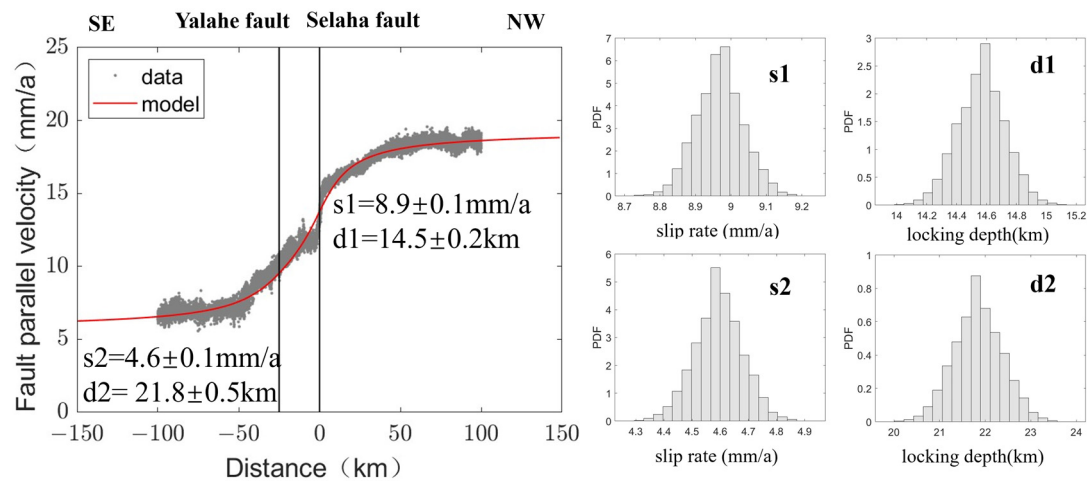


Figure 6. Kinematic parameters and probability density distributions of the Yalahe and Selaha faults in the Kangding segment. The S1 and d1 parameters are associated with the Selaha fault, while the S2 and d2 parameters correspond to the Yalahe fault.

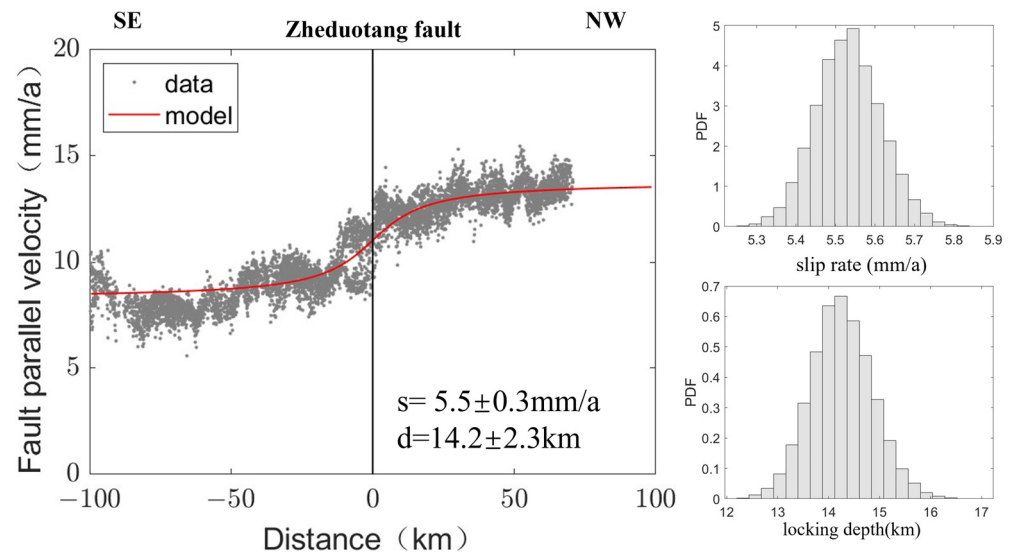


Figure 7. Kinematic parameters and probability density distribution of the Zheduotang fault in the Kangding segment.

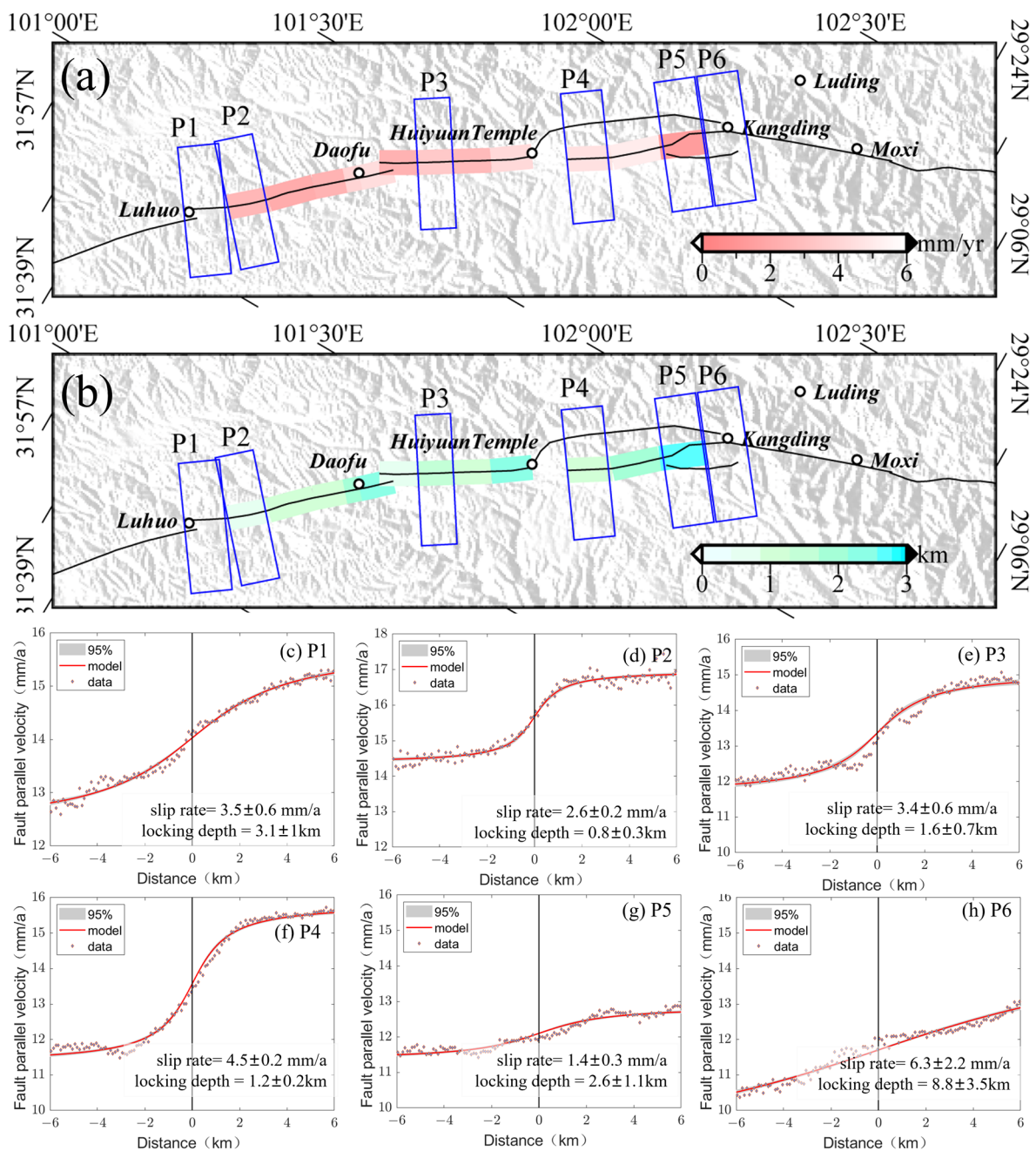


Figure 8. The slip rate and locking depth of the creep section of the XSHFZ. (a) slip rate; (b) locking depth; (c) the velocity profile of P1; (d) the velocity profile of P2; (e) the velocity profile of P3; (f) the velocity profile of P4; (g) the velocity profile of P5; (h) the velocity profile of P6.

5. Discussion

5.1. Reliability Analysis of 3D Deformation Fields Obtained from Different Data

To validate the reliability of the three-dimensional deformation field results, GNSS horizontal and leveling vertical deformation velocities were used to assess the accuracy of the three-dimensional deformation field. Through comparison, it was found that the standard deviations of residuals in the east–west, north–south, and vertical deformation fields were 1.2 mm/yr, 1.4 mm/yr, and 0.88 mm/yr, respectively. Figure 9 depicts both the probability distribution of residuals and a comparison between observed values and results from the integrated GNSS-InSAR three-dimensional deformation field analysis. The fusion

approach demonstrates robustness in obtaining reliable three-dimensional deformation field measurements.

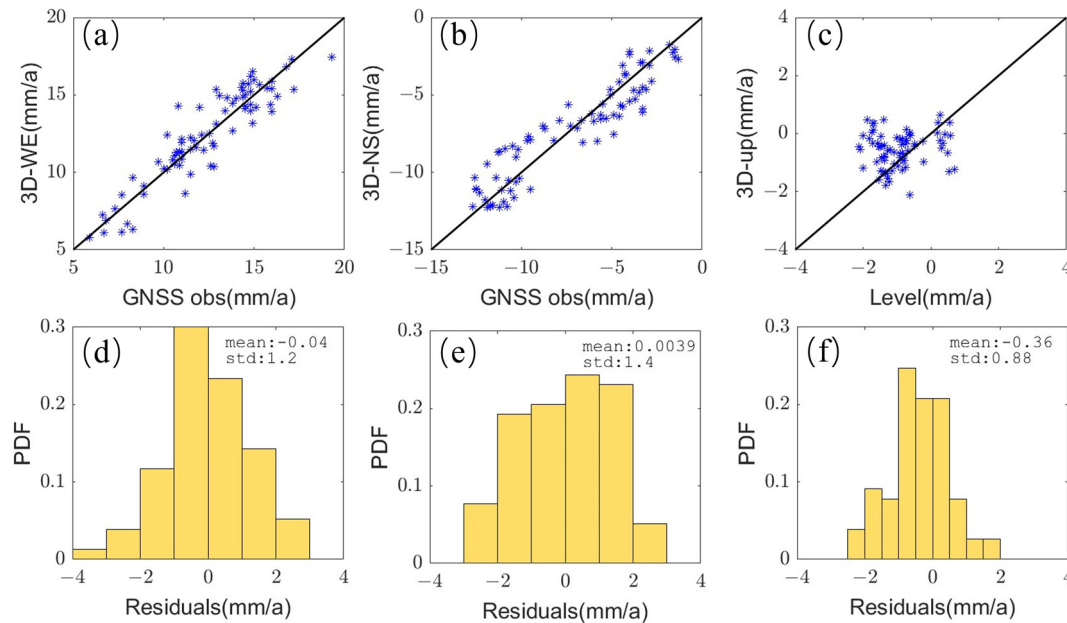


Figure 9. The observed and computed values of three-dimensional deformation field and the probability density distribution of their residuals. (a) Comparison of calculated east-west deformation rate with observed GNSS east-west deformation rate; (b) Comparison of calculated North-South deformation rate with observed GNSS North-South deformation rate; (c) Comparison of calculated vertical deformation rate with observed Leveling deformation rate; (d) Probability distribution of residuals of the east-west deformation rate; (e) Probability distribution of residuals of the north-south deformation rate; (f) Probability distribution of residuals of the vertical deformation rate.

5.2. Slip Partitioning Along the Xianshuihe Fault Zone

Regarding the study of slip rates in the XSHFZ, they can generally be classified into three categories based on time scales (annual scale, millennial scale, and million-year scale) and into two categories based on technical means (those using geodetic data and those using seismological data). Slip rates obtained from geodetic data such as GNSS and InSAR primarily indicate the current slip rates of the fault zone. The period considered is relatively short, typically ranging from several years to several decades. Slip rates since the Late Quaternary (millennial scale) are primarily determined by the fault features of tectonic landforms and the ages of landforms calculated through geochronology. Slip rates at the geological time scale (million-year scale) are mainly derived from the geological offsets and the ages of the corresponding faulting events. By summarizing the existing reports on the slip rates of the XSHFZ, we find that there are different understandings regarding the spatial variation in fault slip rates, primarily characterized by three viewpoints. One viewpoint suggests that the slip rate of the XSHFZ gradually decreases from northwest to southeast [1,2,40]; another proposes that the slip rate increases from north to southeast [7,16,30]. Additionally, some research findings indicate that the slip rates of different segments of the XSHFZ are ~ 10 mm/yr [3,19]. The slip rate results obtained from this study suggest that the average slip rates of the Luhuo, Daofu, Qianning, Kangding, and Moxi segments are 11.5 ± 0.4 , 11.5 ± 0.2 , 13.2 ± 0.3 , 13.6 ± 0.2 , and 10.1 ± 0.1 mm/yr (Figure 10). The Qianning and Kangding segments have the highest slip rates, followed by the Luhuo and Daofu segments, while the Moxi segment exhibits the lowest slip rate.

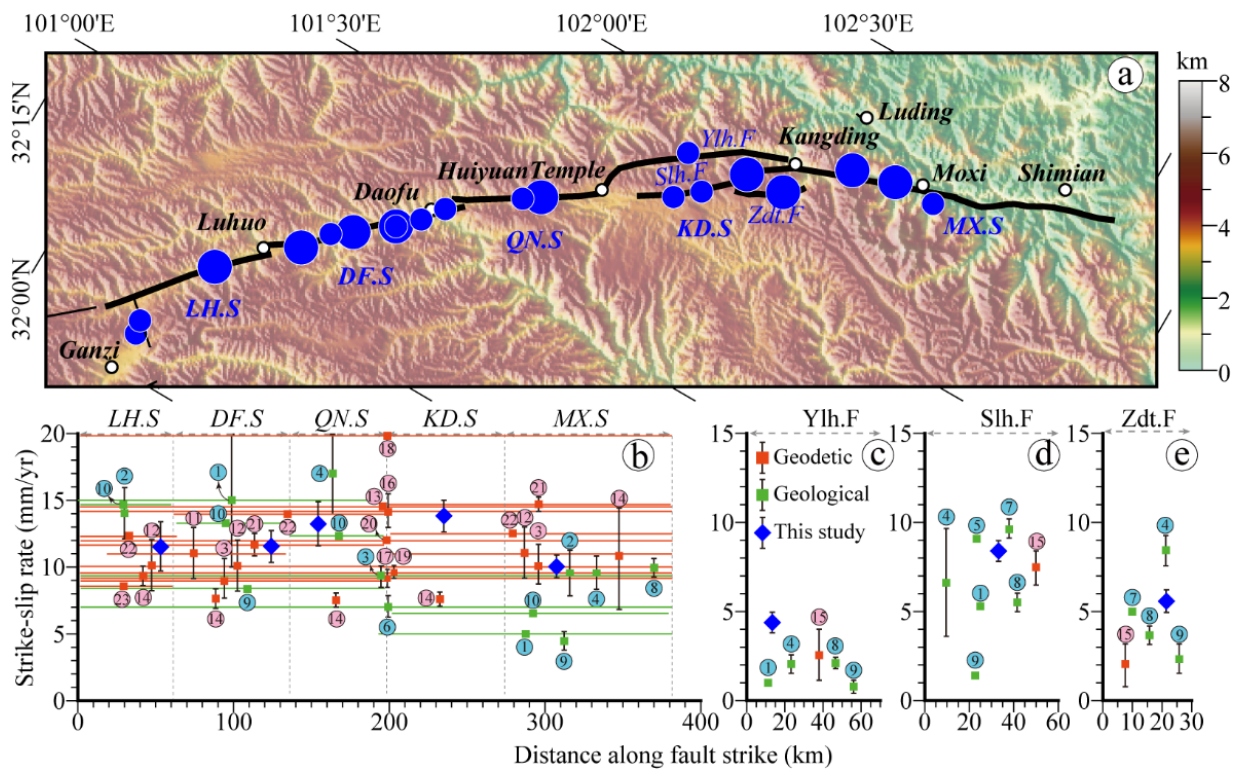


Figure 10. The strike-slip rate of the XSHFZ was reported in different studies. (a) Location of faults; (b) The spatial distribution of the slip rate along the XSHFZ; (c–e) represent the slip rate of the Yalahe, Selaha and Zheduotang faults, respectively. The slip rates come from the following: 1 Allen et al. [1]; 2 Xu et al. [2]; 3 Zhang et al. [3]; 4 Chen et al. [4]; 5 Yan and Lin [5]; 6 Zhang et al. [6]; 7 Bai et al. [7]; 8 Zhou et al. [8]; 9 Liang M.J. [9]; 10 Wen X.Z. [10]; 11 Wang et al. [13]; 12 Shen et al. [14]; 13 Gan et al. [15]; 14 Jiang et al. [16]; 15 Li et al. [17]; 16 Wang et al. [18]; 17 Zheng et al. [19]; 18 Mead et al. [20]; 19 Wang and Shen. [21]; 20 Qiao et al. [22]; 21 Wang et al. [23]; 22 Chen et al. [24]; 23 Xu et al. [25].

The slip rates of the XSHFZ obtained from different observation techniques also exhibit significant differences. Slip rates obtained from geodetic data are concentrated within the range of 7–15 mm/yr [13–25]. Some research studies show relatively higher slip rates, which may be attributed to relatively sparse early geodetic data. For instance, Meade [20] obtained a slip rate of approximately 20 mm/yr for the XSHFZ using block models based on an early sparsely distributed GNSS velocity field. However, utilizing the same method with the latest data, the slip rates for the fault zone are reported to be in the range of 12–15 mm/yr [23,24]. Slip rates obtained from seismological data are primarily concentrated between 5 and 10 mm/yr (Figure 10), except for a few higher slip rates. Allen et al. [1] provided a slip rate of 15 ± 5 mm/yr for the northwestern segment of the XSHFZ based on tectonic geomorphology offsets and radiometric dating results. Additionally, Wang et al. [11] even proposed a slip rate of 30 mm/yr. Zhang et al. [3] summarized the offsets of various segments and reviewed the corresponding age results to propose a slip rate of 9.5 ± 1.5 mm/yr for the XSHFZ since the Late Quaternary. The geomorphic offsets resulting from long-term tectonic movements in the XSHFZ are generally consistent across different studies. The reason for variations in slip rates mainly lies in the determination of the ages when these offsets occurred.

Fault zones exhibiting creep behavior typically demonstrate long-term slow slip and continuous release of tectonic stresses, and are often associated with numerous microseismic events. Such fault zones are less prone to experiencing large earthquakes [68–70]. Since Allen [1] conducted an analysis of creep deformation in the Daofu segment of the XSHFZ based on interseismic deformation observations (Xialatuo Site), researchers have started paying attention to the creep characteristics of the XSHFZ. Zhang et al. [28] analyzed

data from longer observation periods of interseismic deformation and concluded that the Daofu segment of the XSHFZ exhibits significant creep characteristics, while no evidence of creeping motion was found in the Qianning segment. In the past 20 years, studies using geodesy (InSAR and GPS) have shown that almost all segments of the XSHFZ exhibit shallow creep deformation behavior [16,22,30,71]. Our research results suggest that the creep motion in the XSHFZ is primarily concentrated in the Daofu, Qianning, and Kangding segments of the XSHFZ. Based on historical data regarding significant earthquakes, the seismic activity in the Qianning and Kangding segments appears to be relatively low. This trend could be linked to the presence of creep motion within these specific segments.

5.3. Earthquake Hazard Assessment Along the XSHFZ

During an earthquake cycle, the seismic moment accumulation on a fault zone tends to balance with the amount of release [72]. The long-term potential earthquake hazard of a fault zone can be evaluated based on the principle of moment equilibrium, which assesses the relationship between the accumulation rate and the release rate of seismic moments [73]. The magnitude of a potential earthquake on a given fault zone can be further estimated from the seismic moment deficit.

The seismic moment accumulation rate M_0^a of each segment of the XSHFZ accompanied with creep motion can be obtained by Equation (2) [74].

$$M_0^a = \mu L(V_i d_1 - V_c d_2) \quad (2)$$

where L is the length of the fault segment; V_i and V_c are the long-term slip rate and creeping rate during the interseismic period; d_1 is the locking depth; d_2 is the bottom depth of the creeping movement; μ is the shear modulus, typically taking the value of 30 GP.

The seismic moment release on a fault zone can be obtained using Equation (3) [75].

$$M_w = \frac{2}{3} \log M_0^r - 6.03 \quad (3)$$

where M_0^r is the seismic moment released by one earthquake and M_w represents the moment magnitude. The surface wave magnitudes are commonly used in China to represent earthquake magnitudes. However, the seismic moment release can be estimated by incorporating magnitudes from all seismic catalogs as the actual calculation's moment magnitude [76,77], based on previous research findings that suggest a minimal difference between M_w and M_s [78].

The completeness and reliability of a strong earthquake catalog are essential for accurately estimating seismic moment release and seismic moment deficit, and analyzing the background of seismic hazard in a region. Previous studies have indicated that the earthquake catalog for events of M_s 6.5 or higher since 1725 [41] and for events of magnitude 6 or higher since 1879 [35,79] in the XSHFZ is complete. Based on the above earthquake catalog (Table S1), combined with the geometric lengths, slip rates, and locking depths of each fault segment, the seismic moment accumulation and release for each fault segment were calculated and analyzed (Figure 11a,b). Subsequently, the seismic moment deficit and the corresponding potential earthquake magnitudes were calculated (Figure 11c). The results indicate that the five segments of the XSHFZ have a potential risk of earthquakes with magnitudes of 6.5 or higher. The segments of Luhuo, Daofu, and Moxi in the XSHFZ are still in a phase of seismic moment surplus, lacking sufficient seismic moment accumulation for strong earthquakes in the short term. However, the Qianning segment, the Yalahe fault, and the Selaha fault (Kangding segment) pose risks of earthquakes with magnitudes of 6.9, 6.9, and 6.6, respectively. The results are generally in line with the research conducted by Wang et al. [76]. However, there are slight differences in our interpretation of the Daofu segment and the Moxi segment compared to the findings presented by Qiao et al. [30] and He et al. [66]. Previous studies mainly concentrated on determining the moment magnitude related to energy accumulation since the latest large earthquake, without considering the

notion of the earthquake cycle. In contrast, the results in this study cover a more extensive timeframe, ranging from the beginning of a comprehensive earthquake catalog until the present day. Moreover, the results are in good agreement with the seismic gaps located on the XSHFZ, as illustrated in Figure 2, which coincidentally fall within the Qianning and Kangding segment. It is important to monitor the seismic hazard in the two segments in the future. The strain rate field derived from geodetic data can indicate the buildup of strain in a region. According to the strain rate results [80], regions with high strain rates are identified at the junction of the Qianning and Kangding segments, signifying the accumulation of substantial strain energy and emphasizing the seismic hazard in this area. This observation aligns with the conclusions drawn in the present study.

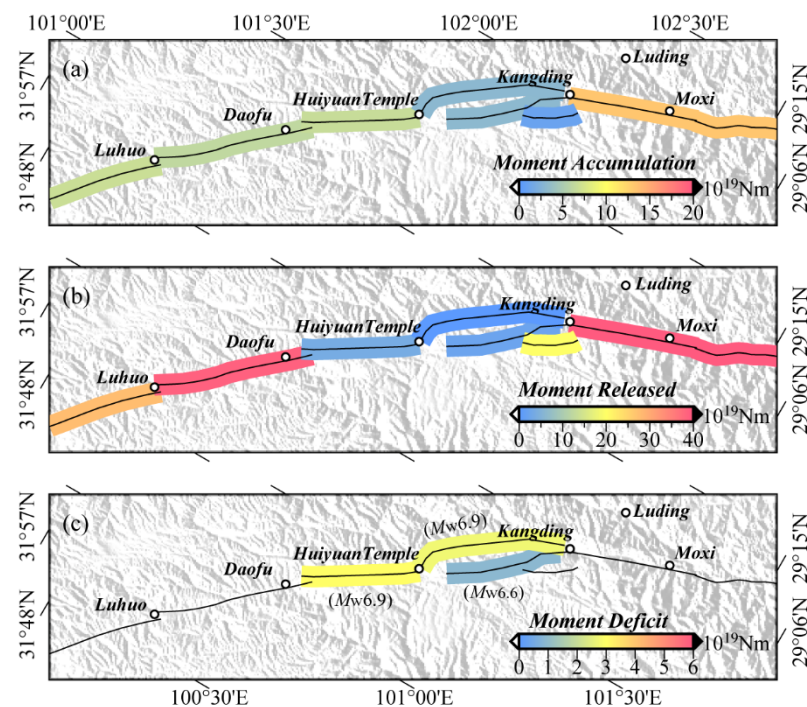


Figure 11. Seismic moment accumulation (a), seismic moment release (b), and seismic moment deficit correspond to strong earthquake magnitudes (c) in the XSHFZ.

6. Conclusions

This paper acquired the three-dimensional deformation field in the XSHFZ and its neighboring regions by integrating GNSS and InSAR velocity fields. The GNSS horizontal and vertical deformation velocities were used to evaluate the accuracy of the three-dimensional deformation field, and the residual standard deviations of the east–west deformation field, north–south deformation field, and vertical deformation field were 1.2 mm/yr, 1.4 mm/yr, and 0.88 mm/yr, respectively. Additionally, by utilizing the dislocation model and the Bayesian Monte Carlo inversion method, we further deduced the kinematic deformation characteristics of the XSHFZ. The kinematic deformation characteristics of the XSHFZ show distinct segmentation. In the middle segment of the XSHFZ, the slip rate is higher than at the two ends, with the Kangding segment having the highest average slip rate of 13.6 ± 0.2 mm/yr, while the Moxi segment has the lowest average slip rate of 10.1 ± 0.1 mm/yr. Creeping motion in the XSHFZ is concentrated between the southeast of Daofu and the northwest of Kangding, with creeping rates ranging from 1.4 to 5.1 mm/yr and depths varying between 0.5 and 3.0 km. The locking depths of the fault zone range between 13 and 26 km, with the Qianning, Kangding, and Moxi segments exhibiting higher locking depths compared to the Luhuo and Daofu segments. In the Kangding segment of the XSHFZ, kinematic deformation is allocated to three branches: Yalahe, Selaha, and Zheduotang faults. Based on the principle of seismic moment balance, the seismic hazard

of each segment of the XSHFZ was analyzed. The results indicate that the high seismic hazard areas in the XSHFZ are consistent with the distribution of seismic gaps along the fault. The Qianning segment and the Yalahe and Selaha faults in the Kangding segment, where seismic gaps exist, pose risks of earthquakes with magnitudes of 6.9, 6.9, and 6.6, respectively. It is recommended to maintain vigilance and conduct continuous monitoring of the seismic hazard in this region in the future.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app142311084/s1>, Figure S1: Gray histograms show the posterior probability density function (PDF) of the slip rate(θ_1) and locking depth(θ_2); Figure S2: Gray histograms show the posterior probability density function (PDF) of the slip rate and locking depth of the shallow creep fault; Table S1: Table S1 Earthquakes of $7.0 > M \geq 6.0$ since 1900 and $M \geq 7.0$ since 1700 had happened on the XSHFZ.

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