

## Research Paper

# Analysis of the GNSS deformation of the 2025 Xizang Dingri M6.8 earthquake



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## ABSTRACT

The study utilized GNSS observation data from 1999 to 2024 to investigate the crustal deformation characteristics near the epicenter of the Dingri earthquake. The results show that the GNSS horizontal velocity value at the Dingri earthquake epicenter is about 25.9 mm/year, and the vertical velocity value is close to zero. The vertical velocity field indicates that most of the study area is subsiding, while the rift area is uplifting, and the Shenzha-Dingjie fault zone is in an uplifting area with a significant uplift gradient. The maximum shear strain rate and the second invariant of the strain tensor at the epicenter are  $36 \times 10^{-9}$ /year and  $56 \times 10^{-9}$ /year, respectively. The surface expansion rate field suggests that the earthquake occurred in a region of compressive deformation. The historical earthquake stress change distribution indicates that the Coulomb stress change loading value at the epicenter of the Dingri earthquake is 1.549 bar, exceeding the stress triggering threshold. This indicates that historical earthquakes promoted the occurrence of this event. The central and western sections of the South Tibetan Detachment System fault zone and the middle section of the Shenzha-Dingjie fault zone are located in high-strain value areas and postseismic stress loading regions. The seismic risk in this region should be closely monitored in the future.

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## 1. Introduction

On January 7, 2025, an M6.8 earthquake occurred in Dingri County, Rikaze City, Xizang. The epicenter was located at 28.36°N, 87.44°E, with a focal depth of 10 km. According to the focal mechanism solution provided by the United States Geological Survey (USGS), this seismic event was a normal-faulting earthquake. This seismic event serves as a typical manifestation of the complex tectonic activities in the Qinghai-Xizang Plateau, whose tectonic context is closely associated with the northeastward movement of the Indian Plate and its collision with the Eurasian Plate. This collision has resulted in crustal shortening and uplift in the region, giving rise to the

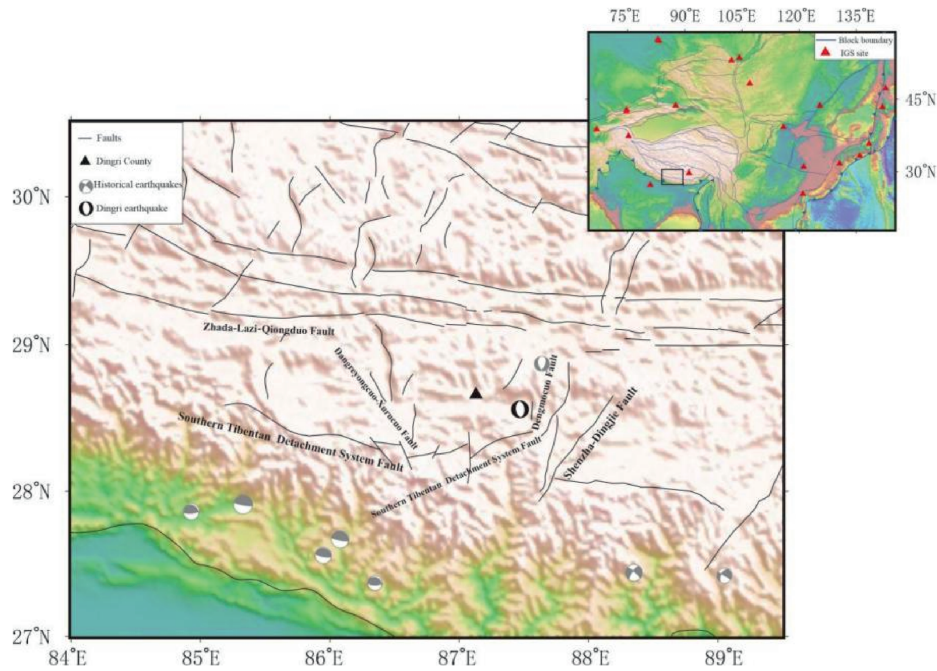
formation of the present-day Qinghai-Xizang Plateau. With the continuous northward compression of the Qinghai-Xizang Plateau, the internal materials have also been constantly escaping eastward, forming a complex tectonic system [1]. A series of north-south-trending tectonic belts has developed in this region [2], among which the Shenzha-Dingjie Fault Zone constitutes a major segment of the Southern Tibetan Detachment System Fault Zone [3] (Fig. 1). This fault zone exhibits frequent tectonic activities, with frequent and intense seismic events occurring in recent years. For example, earthquakes with magnitudes exceeding 5 occurred in 2015, 2016, and 2020, and their focal mechanism solutions all indicated normal-faulting events [4,5], consistent with the type of the Dingri earthquake. The frequent occurrence of normal-faulting earthquake event indicates that this region is under an active extensional tectonic environment and serves as a key area for studying the internal tectonic deformation of the Qinghai-Xizang Plateau.

As a high-precision geodetic technique, Global Navigation Satellite System (GNSS) has been widely applied in seismic

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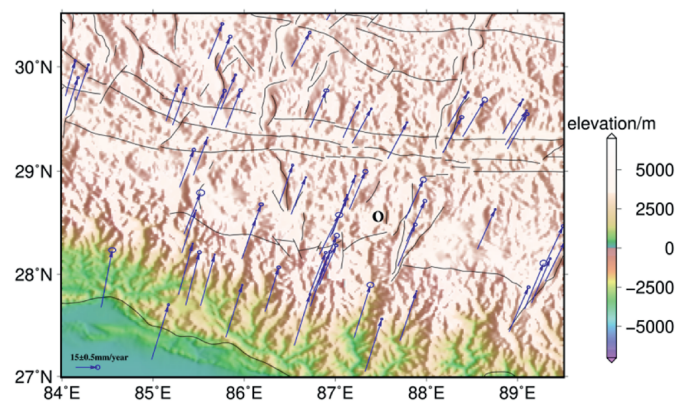
**Fig. 1.** Tectonic background map of the Dingri earthquake region (Gray beach balls represent  $M \geq 6.0$  earthquakes from 1976 to 2024, with data sourced from GCMT. The black beach ball denotes the Dingri M6.8 earthquake on January 7, 2025. ZLQF: Zha-Lazi-Qionghuo Fault; DXF: Dangrengongcuo-Xurucuo Fault; STDSF: Southern Tibetan Detachment System Fault; DMCF: Dengmocu Fault; SDF: Shenzha-Dingjie Fault).

deformation analysis. It can real-time and continuously monitor crustal movements, providing critical data support for studying preseismic, coseismic, and postseismic deformations. Through GNSS deformation analysis, researchers can gain in-depth insights into earthquake rupture processes, aftershock activities, and the dynamic response of the crust, thereby revealing the physical mechanisms and tectonic settings of earthquakes. By analyzing the GNSS deformation data of the Dingri earthquake, this study aims to not only investigate the tectonic deformation mechanisms in this region but also further explore seismic source parameters, fault activity characteristics, and the impact of the earthquake on surrounding areas. This research holds significant scientific and practical value for understanding the internal tectonic deformation processes of the Qinghai-Xizang Plateau, assessing seismic hazard risks, and formulating earthquake prevention and mitigation strategies.

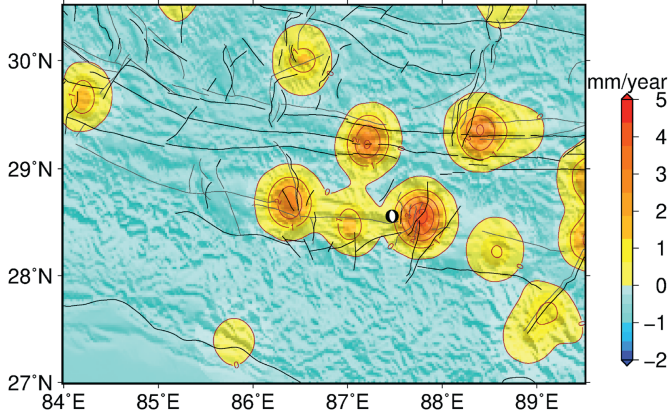
## 2. GNSS data and velocity field

The GNSS data used in this study were primarily sourced from the Chinese Continental Tectonic Environment Monitoring Network (Crustal Movement Observation Network of China, CMONOC) and the China Crustal Movement Observation Network (Network Engineering). The GNSS data were preprocessed using the Bernese 5.4 software, a high-precision professional GNSS data processing tool. We chose Bernese 5.4 for GNSS data processing primarily due to its superior precision in handling complex geodetic scenarios, particularly in high-precision baseline estimation and ionospheric/tropospheric correction modeling—key requirements for our study focusing on crustal deformation analysis. In this study, a unified processing strategy was employed for all GNSS datasets [6] to ensure the accuracy and internal consistency of the derived coordinate solutions. In order to incorporate the daily solution into the ITRF2014 reference framework, 20 IGS reference stations located around the Chinese mainland were

included in the processing for combined solutions (Fig. 1), yielding single-day station coordinates in the ITRF2014 frame. Seismic events can alter the magnitude and direction of station movement velocities in the coordinate time series. To obtain long-term tectonic movement velocities of stations [7], coseismic deformations of major earthquakes were estimated and removed when deriving velocity rates from coordinate time series. Constrained by the global plate motion model in the ITRF2014 frame, the latest GNSS horizontal velocity field (Fig. 2) and vertical velocity field (Fig. 3) of the study area from 1999 to 2024 relative to the Eurasian Plate were obtained. A total of 63 GNSS stations are used in the study area, including 4 continuous stations and 59 campaign stations from the CMONOC. The average velocity of GNSS stations in the study area in the east direction is 10.964 mm/year, the average velocity in the north direction is 27.341 mm/year, and the overall average rate is 29.552 mm/year.



**Fig. 2.** Distribution map of the regional GNSS horizontal velocity field.



**Fig. 3.** Distribution map of the regional GNSS vertical velocity field (Gray lines represent contour lines. The black beach ball denotes the Dingri M6.8 earthquake on January 7, 2025).

Based on the characteristics of the GNSS horizontal velocity field shown in Fig. 2, the study area exhibited a significant northeastward crustal movement trend prior to the Dingri earthquake. The GNSS horizontal velocity at the epicenter reached 25.9 mm/a, indicating a relatively high motion rate. This deformation pattern is closely related to the unique tectonic setting of the region. As the tectonic front zone where the Indian Plate pushes northeastward into Eurasia, the study area simultaneously experiences the lateral extrusion effect of the Himalayan orogenic belt and the eastward material flow of the Qinghai-Xizang Plateau, forming a high-strain accumulation zone at the typical continent-continent collision boundary, which leads to the observed significant crustal deformation characteristics. Notably, the epicenter exhibits a unique positional attribute in the vertical deformation field (Fig. 3), precisely located near the zero-value line of the GNSS vertical movement rate. This boundary line represents a transition zone between tectonic uplift and subsidence. The spatial coupling of high-rate horizontal motion and the vertical deformation transition zone indicates that the source region was in a complex strain accumulation state before the earthquake occurred. However, given the restricted precision of GNSS vertical velocity fields, only qualitative analyses of tectonic activity characteristics can be feasibly carried out. As a result, precisely quantifying the influence of vertical deformation on earthquake nucleation remains a formidable challenge. Nevertheless, these data can efficiently mirror regional uplift or subsidence trends, which are then manifested in the strain field.

### 3. Methodology and theory

#### 3.1. Least squares configuration method

There are various methods for solving and calculating GPS strain fields. Wu et al. (2011) [8] compared multiple analytical calculation methods and concluded that the least squares collocation method can well balance the relationship between data stability and resolution. The optimal estimation results of the least squares collocation method can effectively address the issue of uneven weights at different locations caused by the inhomogeneous spatial distribution of GPS stations. They can be consistent with the distribution characteristics of GPS stations [9]. Based on the principle of least squares collocation, a unified motion model is used to describe crustal movements based on different reference datums, that is, a unified velocity field model is constructed [10,11]. The theoretical formulas are as follows:

$$\mathbf{V}_o = \mathbf{A} \mathbf{\Omega} + \mathbf{U} \mathbf{V}_s + \Delta \quad (1)$$

$q \times 1 \quad q \times 3 \quad 3 \times 1 \quad q \times m \quad m \times 1 \quad q \times 1$

In Eq. (1),  $\mathbf{V}_o$  represents the GPS horizontal observation velocity vector, typically the velocity in the ITRF reference frame;  $\mathbf{A}$  is the coefficient matrix composed of the coordinate information of observation stations,  $\mathbf{\Omega}$  is the Euler parameter vector;  $\mathbf{U}$  is the coefficient matrix of known parameters, which describes the way that known parameters influence the observed values;  $\mathbf{V}_s$  represents the remaining velocity after subtracting the rigid motion (after noise filtering) from the observation velocity  $\mathbf{V}_o$ .  $\mathbf{V}_s$  is continuously distributed in the spatial domain;  $\Delta$  is the random error in the observed velocity, the values of  $\mathbf{\Omega}$ ,  $\mathbf{V}_s$  and the covariance  $C$  can be solved.

Based on the assumption of continuous crustal deformation, the velocity correlation between two stations that are close in space must be high, and vice versa. We use the Gaussian-type covariance function to represent the relationship that the covariance of the observed signals between different stations decreases as the distance between the stations increases. As shown in the following formula:

$$C(d) = C(0) \exp(-k^2 d^2) \quad (2)$$

In Eq. (2),  $d$  denotes the distance between observation points,  $C(d)$  is the covariance value,  $C(0)$  and  $k$  are undetermined parameters, which are calculated through nonlinear fitting based on the statistical computation of the velocity field.

#### 3.2. Coulomb stress model

The Coulomb stress ( $\Delta CFS$ ) is a core theoretical tool in the interdisciplinary field of seismology and rock mechanics, which is used to quantitatively describe the influence of changes in stress state on fault slip (earthquake triggering or inhibition). Since it is difficult to obtain the absolute stress state of the crust [12], seismologists have derived the commonly used expression of  $\Delta CFS$  through a series of assumptions [13–15].  $\Delta CFS$  calculation formula is as follows [16]:

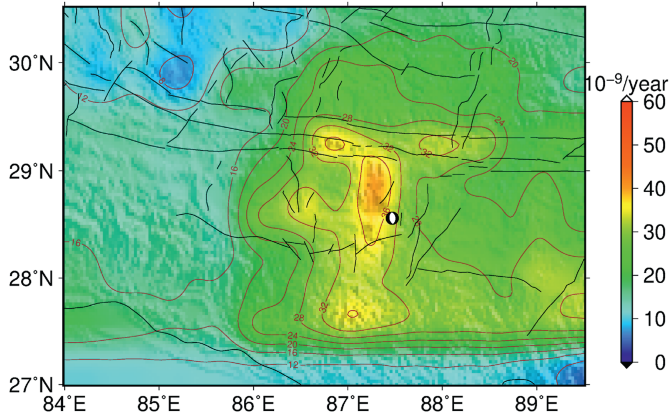
$$\Delta CFS = \Delta \tau + \mu' \Delta \sigma_n \quad (3)$$

where  $\Delta \tau$  represents the change in shear stress on the fault plane, which is consistent with the slip direction of the fault;  $\Delta \sigma_n$  denotes the change in normal stress on the fault plane, with tensile stress taken as positive; and  $\mu'$  is the effective friction coefficient of the fault, which is related to the material properties of the fault medium. The effective friction coefficient has little impact on the spatial distribution characteristics of  $\Delta CFS$ , but it has a certain influence on the value of  $\Delta CFS$  [16,17]. The effective friction coefficient used in this paper is set to 0.4.

### 4. Analysis of strain characteristics in the epicentral region

The horizontal velocity field derived from GNSS data processing provides a direct reflection of the crustal deformation characteristics in this region. However, this velocity field is susceptible to the influence of factors such as the reference frame. To better study the crustal movement characteristics of the region, we employed the least squares collocation method to calculate the strain field based on the horizontal velocity field [18–20]. Based on the horizontal velocity field, we derived the characteristics of the strain field by performing  $0.25^\circ \times 0.25^\circ$  interpolation calculations over the study area using the least squares collocation method. Fig. 4 displays the distribution of the maximum shear strain rate field of





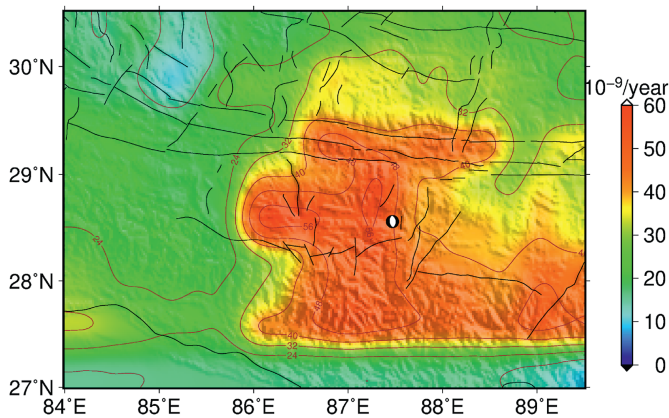
**Fig. 4.** Distribution map of the maximum shear strain rate (Gray lines represent contour lines. The black beach ball denotes the Dingri M6.8 earthquake on January 7, 2025).

the study area, where high-value zones of maximum shear strain rate are primarily concentrated near the northeastern part of Dingri County, and the Dingri earthquake occurred precisely in this region. The maximum shear strain rate at the epicenter is approximately  $36 \times 10^{-9}/\text{year}$ .

Fig. 5 shows the distribution of the second invariant of the strain tensor calculated from the velocity field. The second invariant of the strain tensor is used to measure the overall intensity or magnitude of deformation, and is characterized by its invariance under coordinate system transformations, thus reflecting the intrinsic property of deformation magnitude. In seismic strain analysis, seismic hazard is typically associated with fault activity, stress accumulation, and deformation degree. As a quantitative indicator of deformation intensity, the second invariant of the strain tensor can reflect the degree of deformation concentration within the crust. Regions with high values may correspond to fault zones or areas with intense tectonic activity, where stress concentration is prone to occur. When the accumulated deformation exceeds the strength limit of rocks, earthquakes may be triggered [11,21]. The definition formula of the second invariant of the strain tensor is as follows:

$$\tau_{2\text{inv}} = \sqrt{\tau_{xx}^2 + 2\tau_{xy}^2 + \tau_{yy}^2} \quad (4)$$

Here,  $\tau_{xx}$  represents the strain in the east-west direction,  $\tau_{yy}$  represents the strain in the north-south direction, and  $\tau_{xy}$  is the shear strain.



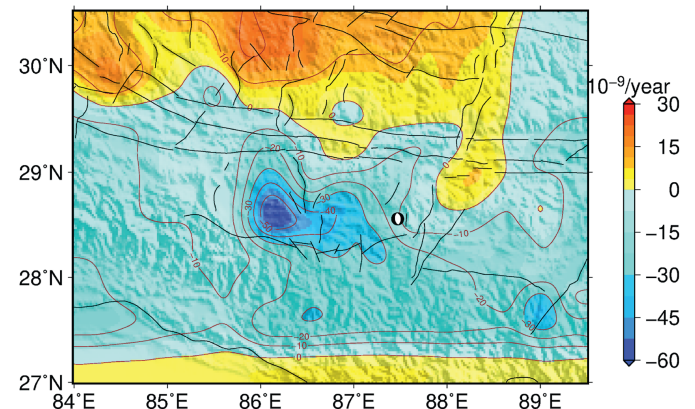
**Fig. 5.** Distribution map of the second invariant of the strain tensor (Gray lines represent contour lines. The black beach ball denotes the Dingri M6.8 earthquake on January 7, 2025).

The distribution of the second invariant of the strain tensor is similar to that of the maximum shear strain rate field, but with generally higher numerical values. As shown in Fig. 5, the high-value areas of the second invariant of the strain tensor are concentrated in the Dangrengcuo-Xurucuo Fault Zone, Dengmecu Fault, and the middle segment of the South Tibetan Detachment System fault zone. Previous studies have indicated that earthquakes tend to occur in or near the region with high strain accumulation [22–24]. The Dingri earthquake is located in the high-value area of the second invariant of the strain tensor, and the value of the epicenter is approximately  $56 \times 10^{-9}/\text{year}$ .

The characteristic of the areal dilation rate near the epicentral region is shown in Fig. 6, where positive values represent surface expansion and negative values represent surface compression. The regional surface expansion rate map reveals that the area is mainly subjected to surface contraction and compression. The high-value area of surface compression is near the southwestern segment of the Dangrengcuo-Xurucuo Fault Zone, the value is approximately  $-50 \times 10^{-9}/\text{year}$ , and the gradient value is relatively large. This is consistent with the results from the joint analysis of gravity and GNSS data [25]. The epicentral region also exhibits surface compression, with a value of approximately  $-20 \times 10^{-9}/\text{year}$ .

## 5. Analysis of the regional stress evolution characteristic

The stress changes on the fault surface before and after earthquakes are typically quantitatively characterized by  $\Delta\text{CFS}$ , which represents the resultant force of shear stress and frictional stress on the fault surface [26]. In recent years,  $\Delta\text{CFS}$  has been widely applied in the research of earthquake stress triggering and stress perturbations along major active faults. Strong earthquakes in adjacent fault zones often interact and influence each other, and the  $\Delta\text{CFS}$  changes caused by coseismic and postseismic deformation can quantitatively describe the interactions between seismogenic faults. Seismic events may induce stress loading on receiver faults through  $\Delta\text{CFS}$  enhancement, thereby reducing the critical failure threshold and advancing the seismic rupture potential. Conversely, stress unloading associated with  $\Delta\text{CFS}$  reduction increases the effective fault strength, retarding the nucleation of subsequent earthquakes by extending the interseismic locking period. The  $\Delta\text{CFS}$  induced by earthquakes can be classified into three categories: static Coulomb stress (coseismic Coulomb stress), dynamic Coulomb stress, and viscoelastic Coulomb stress (postseismic viscoelastic relaxation stress) [26].



**Fig. 6.** Distribution map of areal dilation rate (Gray lines represent contour lines. The black beach ball denotes the Dingri M6.8 earthquake on January 7, 2025).



In order to investigate the influence of the  $\Delta$ CFS of the strong earthquake sequence in the study area on the current Dingri earthquake, as well as the  $\Delta$ CFS changes in this area after the earthquake, we used the PSGRN/PSCMP software [27] to calculate the  $\Delta$ CFS changes in the study area. For  $\Delta$ CFS calculation, parameters such as the regional crustal model of the study area, source fault parameters, and receiver fault parameters are required. The parameters of the Earth's medium in the regional crustal model refer to the literature by Xiong et al. (2015) [28], as shown in Table 1. We adopted the detailed slip distribution published by the USGS to obtain the source fault model. For earthquakes without a detailed slip distribution model, the empirical formulas proposed by Wells and Coppersmith (1994) were used to calculate the length, width, and slip of the source fault [29,30]. The statistical formulas are as follows:

Strike-slip earthquake:

$$\begin{aligned} L &= 10^{0.62M-2.57} \\ W &= 10^{0.27M-0.76} \\ U &= 10^{0.90M-6.32} \end{aligned} \quad (5)$$

Thrust earthquake:

$$\begin{aligned} L &= 10^{0.58M-2.42} \\ W &= 10^{0.41M-1.61} \\ U &= 10^{0.08M-0.74} \end{aligned} \quad (6)$$

In Eqs. (5) and (6),  $L$  and  $W$  represent the length and width of the fault, with units of km.  $U$  represents the average slip of the fault, with units of m.

We collected the seismic data ( $M \geq 6.0$ ) in the study area and found that most of the earthquakes lacked detailed slip distribution information. Therefore, based on the empirical formulas proposed by Wells and Coppersmith (1994) [29], we calculated the source fault model. The specific results are shown in Table 2. The receiver fault parameters were set as the parameters of the Dingri earthquake (strike =  $349^\circ$ , dip =  $42^\circ$ , rake =  $-103^\circ$ ), with a depth of 10 km, and an effective friction coefficient was set as 0.4 [31–34].

Fig. 7(a) shows the coseismic and postseismic Coulomb stress change distribution at a depth of 10 km resulting from historical earthquakes ( $M \geq 6.0$ ) during 1976–2024. The results show that the Dingri earthquake was located in the stress loading zone. The  $\Delta$ CFS loading value at the epicenter was 1.549 bar, which was much higher than the seismic trigger threshold (usually 0.1–1 bar). This suggests the  $\Delta$ CFS of historical earthquakes significantly promoted the occurrence of the Dingri earthquake [12,32,35,36]. The historical earthquakes before the Dingri earthquake showed that the  $\Delta$ CFS in the Southern Xizang of China was mainly loading, especially in the areas near the Dangreongcuo-Xurucuo Fault Zone, the Shenza-Dingjie Fault Zone, and the Southern Tibetan Detachment System Fault Zone, where the stress loading was more obvious. Fig. 7(b) shows the coseismic  $\Delta$ CFS distribution of the Dingri earthquake, with regions far from the Dingri earthquake exhibit minimal stress loading/unloading changes, while closer regions show more significant variations. Notably, the Southern Tibetan Detachment System Fault Zone is situated within a stress shadow zone, indicative of coseismic stress unloading. Conversely, the central-southern segment of the Shenza-Dingjie Fault Zone is located in a stress loading domain, suggesting enhanced seismic hazard potential. Fig. 7(c) shows the distribution of  $\Delta$ CFS 30 years after the Dingri earthquake and historical earthquakes. It can be observed that the area from the Dangreongcuo-Xurucuo fault system to the epicenter of the Dingri earthquake remains in a strong unloading region, where the unloading effect induced by the Dingri earthquake is greater than the loading effect imposed by historical earthquakes. In contrast, intense stress loading effects persist in the middle-western segment of the Southern Tibetan Detachment System Fault Zone and the middle-southern segment of the Shenza-Dingjie Fault Zone, with their stress change values exceeding the seismic stress triggering threshold of 0.1 bar. From the perspective of stress perturbation, the western segment of the Southern Tibetan Detachment System Fault Zone and the central-southern segment of the Shenza-Dingjie Fault Zone warrant attention for their potential seismic hazard in the future.

## 6. Discussion

This paper systematically analyzes the crustal deformation characteristics and  $\Delta$ CFS transfer laws of the 2025 Dingri M6.8 earthquake in Xizang using GNSS observation data. The results provide key constraints for understanding the seismogenic mechanism in the extensional tectonic environment of southern Qinghai-Xizang Plateau, and also inspire further thinking on the regional tectonic dynamic processes.

The horizontal movement rate of the epicenter of the Dingri earthquake reached 25.9 mm/a, and it was in the zero-value transition zone of vertical movement. This feature is highly consistent with the dynamic background of the continuous push of the Indian Plate towards the Eurasian Plate and the eastward

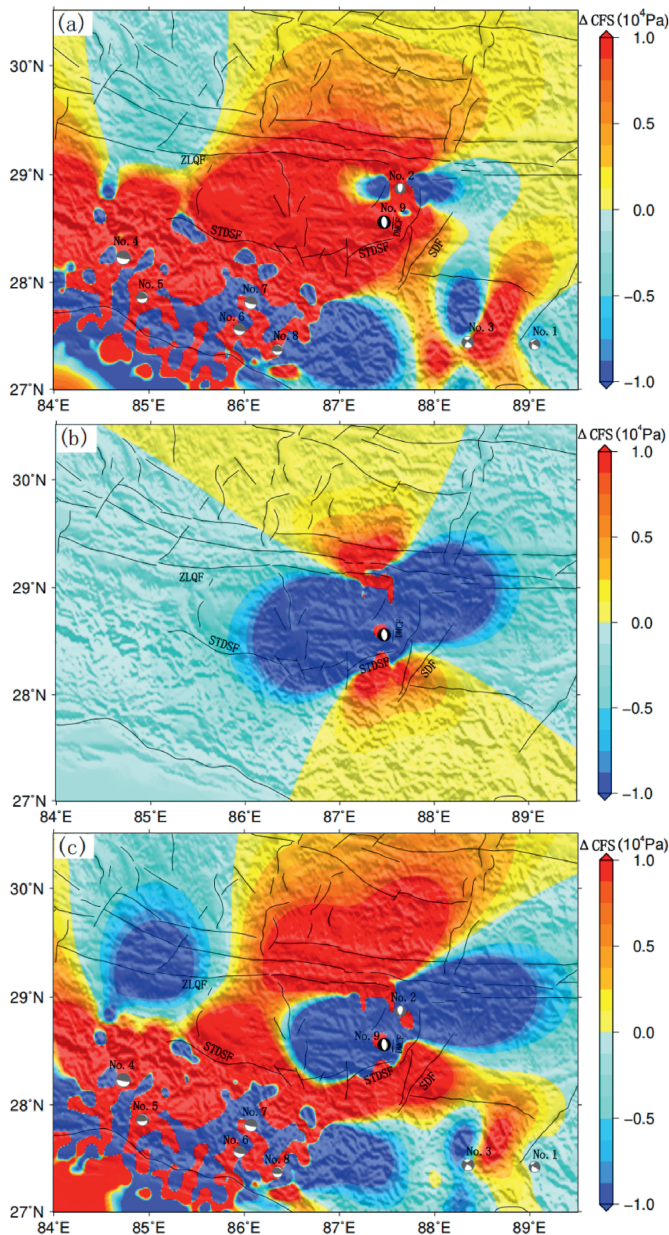
**Table 1**  
Crust and upper mantle hierarchical structure model.

| No. | Depth (km) | $V_p$ (km/s) | $V_s$ (km/s) | Density (kg/m <sup>3</sup> ) | $\eta$ (Pa·s) |
|-----|------------|--------------|--------------|------------------------------|---------------|
| 1   | 0          | 4.50         | 2.60         | 2100                         | 0             |
| 2   | 5          | 5.70         | 3.40         | 2500                         | 0             |
| 3   | 10         | 6.20         | 3.65         | 2680                         | 0             |
| 4   | 20         | 5.60         | 3.30         | 2750                         | 1.0E+19       |
| 5   | 25         | 6.30         | 3.70         | 2950                         | 1.0E+19       |
| 6   | 36         | 6.60         | 4.00         | 3150                         | 1.0E+19       |
| 7   | 45         | 6.00         | 3.40         | 3150                         | 1.0E+19       |
| 8   | 51         | 7.20         | 4.30         | 3350                         | 1.0E+19       |
| 9   | 71         | 8.15         | 4.90         | 3400                         | 1.0E+20       |
| 10  | 98         | 7.40         | 4.30         | 3400                         | 1.0E+20       |

**Table 2**  
Slip distribution models of historical earthquakes.

| No. | Date       | Magnitude | Long (°E) | Lat (°N) | Depth (km) | Strike (°) | Dip (°) | Rake (°) | Length (km) | Width (km) | Strike-slip (m) | Dip-slip (m) | Ref.  |
|-----|------------|-----------|-----------|----------|------------|------------|---------|----------|-------------|------------|-----------------|--------------|-------|
| 1   | 1980-11-19 | 6.3       | 89.05     | 27.42    | 44.0       | 209        | 51      | -2       | 21.162      | 8.639      | 0.543           | 0.019        | [1,2] |
| 2   | 1993-03-20 | 6.2       | 87.64     | 28.87    | 15.0       | 161        | 46      | -121     | 15.585      | 8.786      | -3.100          | 0.515        | [1,2] |
| 3   | 2011-09-18 | 6.9       | 88.35     | 27.44    | 46.0       | 216        | 72      | -12      | 53.253      | 12.912     | 1.318           | 0.280        | [1,2] |
| 4   | 2015-04-25 | 7.8       | 84.73     | 28.23    | 8.2        | 290        | 7       | 101      | 148.355     | 43.209     | -0.683          | -0.785       | [2,3] |
| 5   | 2015-04-25 | 6.7       | 84.93     | 27.86    | 21.0       | 308        | 23      | 131      | 29.084      | 13.656     | -0.683          | -0.785       | [1,2] |
| 6   | 2015-04-26 | 6.7       | 85.95     | 27.56    | 20.6       | 289        | 14      | 98       | 30.397      | 14.089     | -0.151          | -1.071       | [1,2] |
| 7   | 2015-05-12 | 7.3       | 86.07     | 27.81    | 15.0       | 303        | 9       | 110      | 62.168      | 23.364     | -0.921          | -1.808       | [2,3] |
| 8   | 2015-05-12 | 6.2       | 86.35     | 27.37    | 20.1       | 299        | 28      | 116      | 14.260      | 8.252      | -0.244          | -0.500       | [1,2] |
| 9   | 2025-01-07 | 7.1       | 87.38     | 28.60    | 10.0       | 349        | 42      | -103     | 50.956      | 20.300     | 0.059           | 1.703        | [2,3] |

Note: 1. GCMT (<https://www.globalcmt.org/>); 2. Wells and Coppersmith (1994); 3. USGS (<https://www.usgs.gov/>).



**Fig. 7.** Distribution map of  $\Delta\text{CFS}$  on the study area. Black lines represent faults, with their simplified names as shown in Fig.1. The black focal mechanism spheres denote the Dingri earthquake, while the gray focal mechanism spheres represent historical earthquakes with a magnitude of  $M \geq 6$  that occurred from 1976 to 2024. The labels of the focal mechanism spheres and the sources of the earthquake catalog are consistent with those in Table 2, and the size of each focal mechanism sphere corresponds to the magnitude of the earthquake. (a) Distribution map of postseismic  $\Delta\text{CFS}$  effects induced by the eight historical earthquakes prior to 2025 in the study area. (b) Distribution map of coseismic  $\Delta\text{CFS}$  effects induced by the Dingri earthquake in the study area. (c) Distribution map of the impact of postseismic  $\Delta\text{CFS}$  induced by the eight historical earthquakes and the current Dingri earthquake in the study area after 30 years.

escape of materials from the Qinghai-Xizang Plateau. The significant uplift gradient of the Shenzha-Dingjie Fault Zone and the frequent normal-faulting earthquakes in this region (e.g., the 2015 and 2020 events) collectively confirm the active extensional process of the Southern Tibetan Rift System, supporting the model of stress release within the Qinghai-Xizang Plateau through north-south trending graben-horst structures. It is noteworthy that the epicenter is located at the edge of the high-value zones of the

maximum shear strain rate ( $36 \times 10^{-9}/\text{year}$ ) and the second invariant of the strain tensor ( $56 \times 10^{-9}/\text{year}$ ) (Figs. 4 and 5). This is consistent with the conclusion proposed by Jiang et al. (2022) and Zhao et al. (2025) that strong earthquakes mostly occur in or at the edges of high strain zones [11,21], implying significant strain accumulation in this region. The areal dilation rate field shows that the epicenter is situated in a compressive zone (Fig. 6), indicating that the dextral strike-slip movement of the Southern Tibetan detachment system dominates the local compressive setting, while the occurrence of normal faulting events may result from the local stress release of extensional structures within the compressive environment. Furthermore, the InSAR coseismic deformation field reveals that the coseismic deformation is most significant in the northern and middle segments of the seismogenic fault, while it is relatively minor in the southern segment [37]. This further indicates that the dextral strike-slip movement of the east-west trending Southern Tibetan detachment fault zone primarily controls the manifestation of the areal dilation rate field in the region.

$\Delta\text{CFS}$  calculations reveal that historical strong earthquakes induced a stress loading of 1.549 bar at the epicenter of the Dingri earthquake (Fig. 7(a)), which is far beyond the triggering threshold of 0.1 bar. This result confirms the stress transfer effect within the regional strong earthquake sequence. It resonates with the findings of Yue et al. (2025) [32] regarding the stress loading in southern Xizang caused by the aftershocks of the Gorkha earthquake and the background tectonic stress of faults, indicating that seismic activities in this region exhibit significant spatiotemporal correlations. Fig. 7(c) shows the stress distribution 30 years after the earthquake. The middle-western segment of the Southern Tibetan Detachment System and the middle-southern segment of the Shenzha-Dingjie Fault Zone remain under stress loading, and they overlap with the high-strain zones. This provides a clear target area for future seismic hazard assessment, which is consistent with the view emphasized by Jiang et al. (2022) [23] that strain-stress coupling zones are strong earthquake risk points. The study further reveals the complexity of crustal movement in the southern Qinghai-Xizang Plateau, emphasizes the influence of multi-factor coupling on earthquake gestation, and provides an important reference for improving the basis of regional seismic hazard assessment.

This study still has certain limitations. Firstly, the spatial distribution of GNSS stations is uneven, with insufficient density especially at the intersections of fault zones, which may restrict the detailed resolution of strain fields. Secondly, the accuracy of the vertical velocity field is relatively low, making it difficult to quantify the contribution of vertical deformation to the source process. Thirdly, the fault geometric model used in  $\Delta\text{CFS}$  calculations is derived from the statistical relationship formula proposed by Wells and Coppersmith (1994) [29], and there may be some deviations from the actual rupture [30]; moreover, the impacts of aftershocks and background tectonic stress have not been considered. To address these issues, future research could integrate high-resolution InSAR deformation data with broadband seismic network observations to construct a three-dimensional refined fault model. Meanwhile, interdisciplinary data fusion (e.g., gravity and geomagnetism) can be used to improve crustal layering parameters [37], and the influence of  $\Delta\text{CFS}$  loading and unloading caused by aftershocks should be taken into account to enhance the accuracy of stress inversion.

## 7. Conclusions

Based on the GNSS data during 1999–2024, the GNSS velocity field before the Dingri earthquake was obtained using the high-

precision Bernese 5.4 software. The preseismic strain rate field of the study area was then derived using the least squares collocation method. Incorporating the slip distribution of historical earthquakes, Coulomb stress changes in the study area were calculated using the PSGRN/PSCMP software. Through analyzing the GPS deformation characteristics and stress change characteristics in the epicentral area, the following preliminary conclusions were drawn:

- (1) The study area is located at the frontal zone of the collision between the Indian Plate and the Eurasian Plate, where crustal materials are continuously compressed northward and simultaneously extruded eastward. This collisional dynamics manifests in GNSS velocity fields as northeast-oriented horizontal motions. The horizontal velocity value at the epicentral location of the Dingri earthquake is approximately 25.9 mm/year, while the vertical velocity value is close to zero. The vertical velocity field indicates that most areas are dominated by subsidence, whereas the Shenza-Dingjie fault zone lies in an uplift zone with a large uplift gradient.
- (2) The strain rate field analysis indicates that the earthquake occurred in a high-value zone of the maximum shear strain rate and the second invariant of the strain tensor. At the epicenter, the maximum shear strain rate and the second invariant of the strain tensor are  $36 \times 10^{-9}$ /year and  $56 \times 10^{-9}$ /year, respectively. The surface expansion rate field characterization reveals that the epicenter is situated in a compressional regime, demonstrating significant crustal contraction preceding the seismic rupture.
- (3) Based on the focal mechanisms or slip distribution data of historical earthquakes of the study area, we calculated the Coulomb stress changes at the Dingri earthquake hypocenter. The Coulomb stress change value at the epicenter of the Dingri earthquake is 1.549 bar, exceeding the stress trigger threshold, indicating that historical earthquakes promoted the earthquake occurrence.
- (4) The Coulomb stress loading values in the central-western segment of the Southern Tibetan Detachment System Fault Zone and the central-southern segment of the Shenza-Dingjie Fault Zone exceed the stress trigger threshold over the three-decade postseismic period. Additionally, this region exhibits relatively high velocity field values and gradients, with high-value zones of both the maximum shear strain rate and the second invariant of the strain tensor fields also concentrated here. Significantly, these collective observations delineate a mechanically coupled zone characterized by sustained stress accumulation and strain partitioning. Such kinematic and dynamic coherence strongly suggests elevated seismic potential, necessitating priority assessment in regional seismic hazard mitigation strategies.

#### CRediT authorship contribution statement

**Xiaofei Lu:** Writing – original draft, Formal analysis, Conceptualization. **Caihong Zhang:** Software, Data curation. **Kai Tan:** Writing – review & editing, Methodology, Funding acquisition. **Yong Huang:** Resources, Funding acquisition. **Chengtao Li:** Software, Methodology, Data curation.

#### Declaration of competing interest

The authors declare that there is no conflicts of interest.

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