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Source mechanism of the 2023 M_s 5.5 earthquake in Subei, Gansu Province revealed by relocated aftershocks and InSAR: complement to the 'shallow slip deficit' of the eastern boundary of the Altyn Tagh fault

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The M_s 5.5 earthquake struck on 24 October 2023, in Subei County, Gansu Province, China, occurring along the eastern segment of the Altyn Tagh fault. It raises the question of whether this earthquake is linked to the ongoing shortening slip rate along this segment or triggered by other seismic events. Analyzing the fault geometry of the Subei earthquake and understanding the significance of the weakening activity rate for seismic hazards in neighboring regions is crucial. The surface deformation from small- and medium-sized earthquakes (magnitudes less than M_w 5.5) is often subtle, and the coseismic deformation detected by interferometric synthetic aperture radar (InSAR) is vulnerable to atmospheric disturbances, leading to significant measurement errors. Moreover, inaccuracies in the regional crustal velocity structure can cause errors in earthquake localization based on seismic data. These challenges complicate the establishment of a rupture model for seismogenic faults and hinder the inversion of fault slip models. To overcome these limitations, we employed the time-series InSAR stacking method and aftershock relocation to determine the fault geometry of the Subei earthquake. A two-step inversion method was utilized to ascertain both the fault geometry and slip distribution. Our modeling indicates that the 2023 Subei earthquake had a thrust mechanism with a component of strike-slip. The rupture did not reach the surface, with the maximum fault slip measuring 0.45 m at a depth of 2.5–3.5 km. The fault dips westward, and the moment magnitude is calculated at 5.4. This earthquake is associated with the ongoing weakening of the left-lateral strike-slip rupture along the Altyn Tagh fault in the Subei region. Furthermore, retrograde thrust tectonics significantly contribute to the absorption of accumulated stress during this process. Our findings highlight the potential of utilizing time-series InSAR images to enhance earthquake catalogs with geodetic observations, offering valuable data for further studies of the earthquake cycle and active tectonics. This approach is also applicable in other

tectonically active regions, enhancing understanding of seismic hazards and risk assessment.

KEYWORDS

2023 subei earthquake, stacking, altyn tagh Fault, coseismic surface deformation, relocated aftershock, fault geometry

1 Introduction

According to the China Earthquake Network Center (CENC), a M_s 5.5 earthquake occurred on 24 October 2023, in Subei County, Gansu Province, with epicenter coordinates of latitude 39.43°N and longitude 97.275°E and a focal depth of 10 km (Figure 1). The epicenter was located in Shibao Township, Subei County, 119 km away from Shibao Township, 51 km away from Laojunmiao Town in Yumen City, 94 km away from Jiayuguan City, 98 km away from Yumen City, and 109 km away from Jiuquan City. According to reports, the earthquake was strongly felt in Jiayuguan City, Suzhou District of Jiuquan City, Dunhuang City, Guazhou County, Ganzhou District of Zhangye City, and Gaotai County. No casualties or property damage have been reported at this time. The Subei seismic region is located in the western part of the Qilian Mountains seismic zone. Due to regional geotectonic complexity, studies have shown that the slip rate of the eastern section of the Altyn Tagh fault in the Subei area has decreased (Xu et al., 2003). This has led to the formation of the Tanghe Nan Shan, Daxueshan, Qilian Mountains, and other northwest-trending mountain blocks, as well as the development of several retrograde thrust tectonics. Due to the continuous absorption of the northward movement of the Indian plate by the Altyn Tagh fault and the subsequent accommodation of the absorbed slip rate by northwesterly active reverse faults, the study area has experienced frequent earthquakes in the past 50 years. Since seismic records began in 1900, there has been one earthquake of magnitude 7.0–7.9, six earthquakes of magnitude 6.0–6.9, and 23 earthquakes of magnitude 5.0–5.9. During the past 50 years the largest earthquake within 100 km of the Subei epicenter was a magnitude 6.0 event that occurred in Delingha, Qinghai, on 26 March 2022, located 89 km from the current epicenter. Following the earthquake, relevant agencies promptly utilized seismic wave data to determine the focal mechanism solution for the Subei earthquake (Table 1). These results essentially represent measurements of the fault slip behavior at the seismic source. However, there is a certain degree of variability in focal mechanism solutions, posing challenges for making decisions in further establishing earthquake fault models and conducting seismic dynamic analyses. Therefore, further study of the seismic fault characteristics causing the Subei earthquake and exploration of the significance of the weakening activity rate in the eastern segment of the Altyn Tagh fault for seismic hazards in neighboring regions are crucial.

Accurately determining the geometric parameters of seismogenic faults and understanding their movement characteristics are particularly crucial (Ben-Zion, 2008). Research indicates that underground ruptures are not singular but rather complex rupture surfaces, and the geometric characteristics of individual faults and their interactions with faults control the slip distribution and stress patterns and influence the rupture

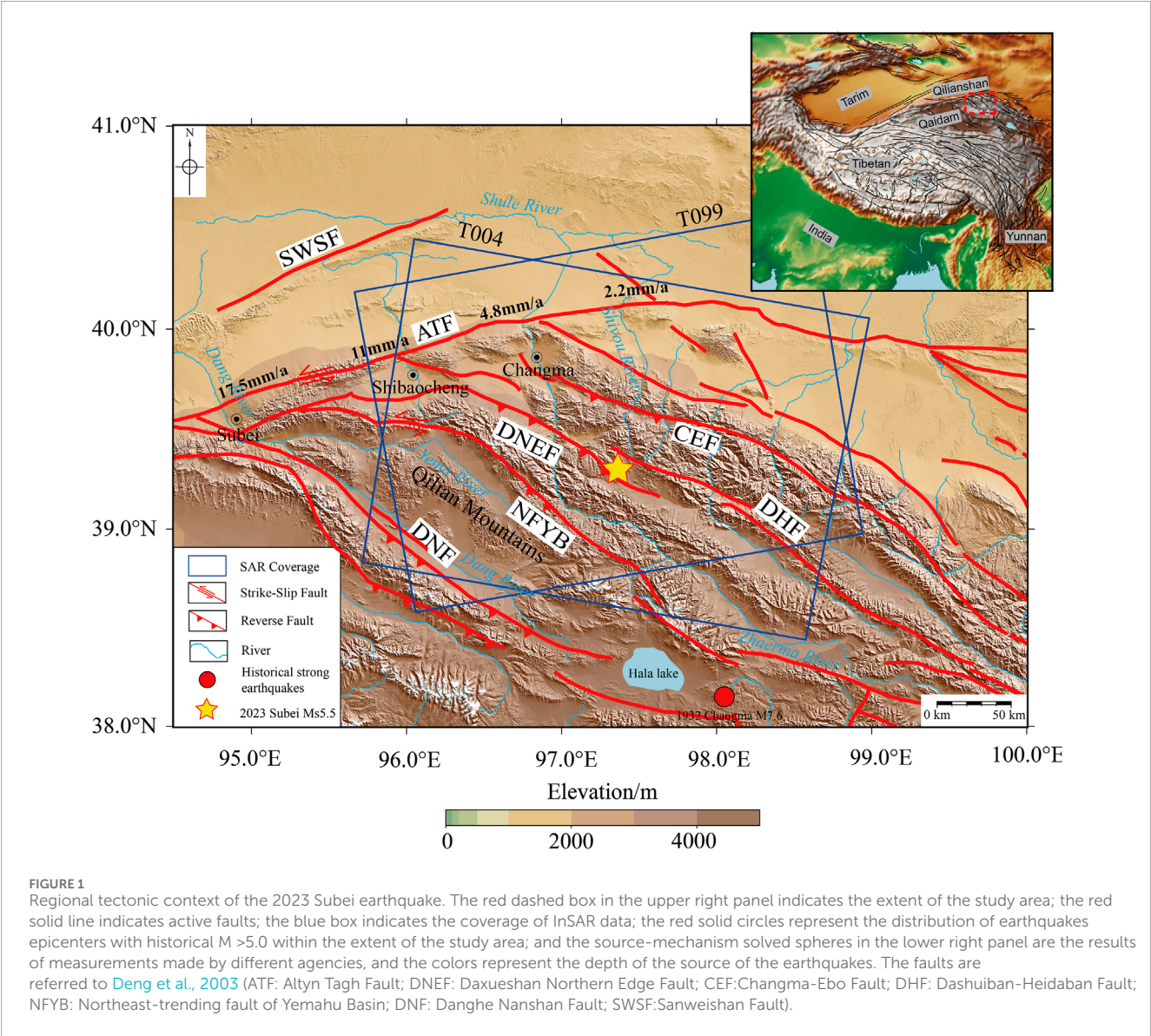
process (Duan, 2019; Nielsen and Knopoff, 1998). Studying the seismic rupture process and fault displacement direction and magnitude is highly important for guiding Earthquake disaster rescue, postdisaster damage assessments, and research on coseismic landslides (Chen et al., 2023). Current research on earthquake rupture processes primarily involves inverting detailed information about the rupture by analyzing seismic waveforms (Hartzell, 1978). With the advancement of global digital seismic networks and seismic source theories, researchers studying earthquake rupture processes on finite faults utilize local strong motion records and teleseismic record data inversion to obtain information such as the scale of earthquake faults, the direction of seismic rupture, and the distribution of slip on fault planes (Zhang et al., 2014; Yang et al., 2022). However, the former requires densely spaced and well-enclosed strong seismic station records, while the latter requires sufficiently large earthquake magnitudes to ensure clear waveform records in the teleseismic direction. These requirements undoubtedly pose greater demands for studying the rupture modes of small to moderate earthquakes, especially those with moment magnitudes (M_w) less than 5.5.

In addition, geodetic data can also be used to infer earthquake rupture processes. Seismic fault models can also be inverted from geodetic data, and the advantage of using geodetic data for earthquake rupture inversion is that less uncertainties are involved, and the inversion results are relatively more stable than those of seismic data inversion (Johnson et al., 1994). Since the 1992 Landers earthquake, interferometric synthetic aperture radar (InSAR) has been widely used in earthquakes and has become an indispensable geodetic tool for the study of coseismic deformation and the inversion of seismic source parameters (Li and Wang, 2023; Luo and Wang, 2022; Liu et al., 2022). As a complement to seismic observation, InSAR imagery provides high-resolution and near-field deformation measurements of the ground surface, which is especially suitable for the deformation of remote seismic zones and sparsely vegetated ground surface areas. However, SAR image interferometry is susceptible to atmospheric influence to some extent, which generates overall deconvolution errors that affect the recovery of the radar line-of-sight (LOS) surface deformation field from the deconvolution of the original interferograms and causes errors in further estimations of the fault-slip distribution. In addition, in the past, when scholars inverted seismic faults, due to the uncertainty of the fault tendency when choosing the seismic source mechanism solution, especially for seismic faults dominated by forward or backlash motion, it was usually difficult to judge the tendency of seismic faults by a single use of InSAR observations. The usual practice is to invert both sets of sections using the solution of the earthquake origin mechanism given by an organization and evaluate the residuals between the observed and simulated values by determining the residuals of the observed and simulated values. In recent years, the use of high-precision

TABLE 1 Solution of the source mechanism of the 2023 Subei earthquake determined by different organizations.

Agency	Epicenter location		Magnitude M_w	Depth /km	Section surface I			Section surface II		
	Longitude (°E)	Latitude (°N)			Strike	Dip	Slip	Strike	Dip	Slip
GFZ	97.42	38.24	5.39	19	153	39	90	331	51	89
USGS	97.299	39.285	5.43	10	168	44	120	309	53	64
CENC	97.28	39.43	5.4	5	170	60	110	313	35	59

[https://geofon.gfz-potsdam.de/eqexplorer/events/gfz2023uvrt/momenttensor\(GFZ\);https://earthquake.usgs.gov/earthquakes/eventpage/us7000l5yp/moment-tensor\(USGS\);https://www.ceaiqp.ac.cn/kydt/280278.html\(CENC\).](https://geofon.gfz-potsdam.de/eqexplorer/events/gfz2023uvrt/momenttensor(GFZ);https://earthquake.usgs.gov/earthquakes/eventpage/us7000l5yp/moment-tensor(USGS);https://www.ceaiqp.ac.cn/kydt/280278.html(CENC).)



small-seismic positioning to determine the fault geometry of rupture zones has been successful in numerous applications, such as using the spatial position of aftershocks to determine fault models, which has become one of the conventional methods for inverting the rupture process of large earthquakes (Ross et al., 2019; Sun et al., 2018; Bagnardi and Hooper, 2018). Then, the joint aftershock fine localization and InSAR surface coseismic deformation field can be used to more accurately determine the

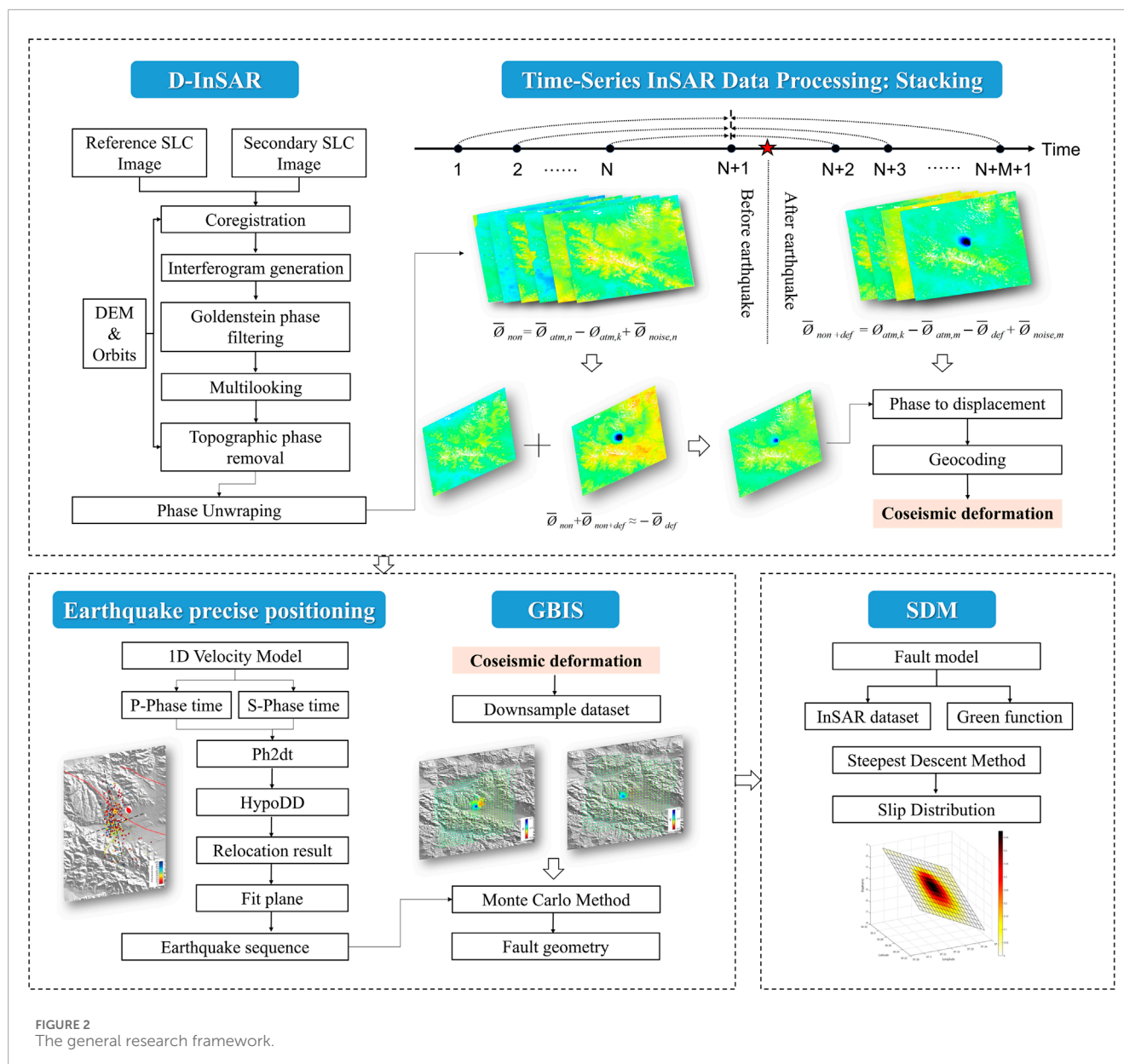


FIGURE 2
The general research framework.

geometric characteristics of the originating faults, which can provide a reliable basis for further determining the slip distribution of the originating faults.

Since the occurrence of the $M_{s5.5}$ Subei earthquake in 2023, no InSAR studies have been conducted on its seismogenic structure. In this study, we first utilized a time series stacking technique based on European Space Agency (ESA) Sentinel-1A satellite data to form interferograms before and after the earthquake, effectively mitigating atmospheric errors through phase unwrapping and stacking. Second, precise localization of aftershock sequences was performed using fixed seismic station data. We employed small fault plane fitting to characterize the geometric features of the seismogenic fault plane and establish a finite seismogenic fault model. Finally, based on ascending and descending line-of-sight (LOS) downsampled datasets, we inverted the slip distribution of this earthquake and calculated the triggering

relationship between the static Coulomb stress change induced by the 2022 Delingha $M_{6.0}$ earthquake and this earthquake. Through these investigations, we gained a better understanding of the deformation field characteristics caused by the Subei earthquake, the seismogenic fault, and the movement properties of the seismogenic fault, thereby exploring the triggering factors of this earthquake.

2 Tectonic background

Due to the strong northward push of the Indian plate, there is a northeastward motion along the northeastern margin of the Qinghai-Tibet Plateau (Xu et al., 2003; Xu et al., 2005). The northern and eastern sides of the Qinghai-Tibet Plateau are also subjected to compression from uplifted blocks, resulting in a series

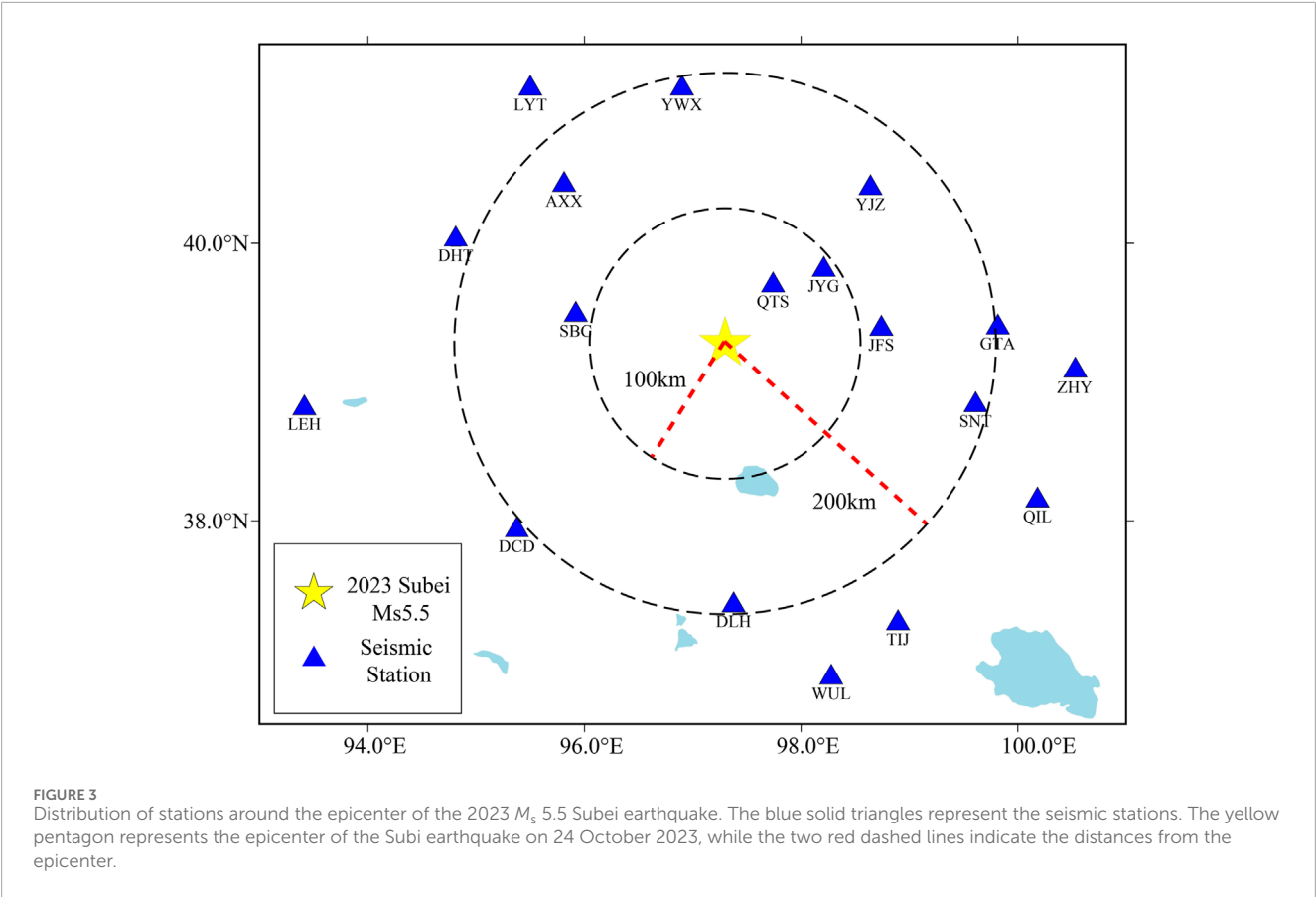


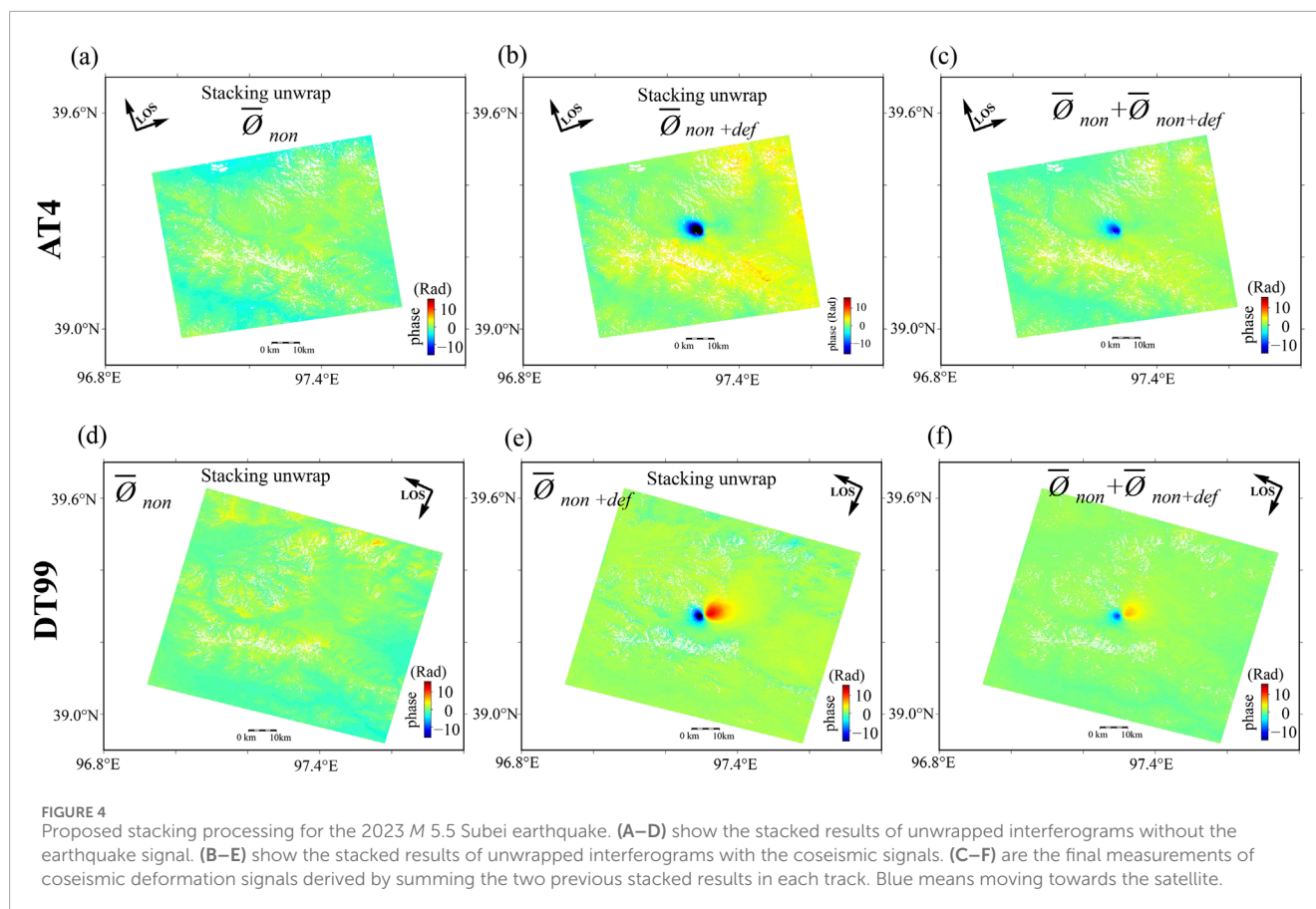
FIGURE 3 Distribution of stations around the epicenter of the 2023 M_s 5.5 Subei earthquake. The blue solid triangles represent the seismic stations. The yellow pentagon represents the epicenter of the Subei earthquake on 24 October 2023, while the two red dashed lines indicate the distances from the epicenter.

TABLE 2 Crustal velocity model of Subei area.

Layer number	V_p (km/s)	V_s (km/s)	Layer top
1	3.90	2.29	0
2	5.90	3.52	4
3	6.25	3.68	18
4	6.62	3.82	29
5	6.74	4.50	42

of neotectonic mountain belts and faults (Elliott et al., 2008; Daout et al., 2018). This motion was hindered by the Alashan and Ordos blocks, which formed the Qilian Mountains seismic zone. Consequently, a series of WNW- to nearly E-W-oriented thrust-slip fault zones have developed, exhibiting south-to-north thrusting with steep-upward and gentlownward geometries. Among these zones, the most influential is the Altyn Tagh fault zone. Its sinistral strike-slip movement and adjacent compressional reverse fault-fold interactions absorb the northward movement of the Indian plate (Ding et al., 2008; Zheng et al., 2013). This directly affects the acceleration of crustal strain rates in the surrounding areas, leading to an increase in seismic activity, making this region prone to frequent strong earthquakes.

The study area is located in the eastern segment of the Altyn Tagh fault. Research indicates that its sinistral strike-slip displacement is transferred and absorbed by the North Qilian Shan thrust reverse fault zone, exhibiting geometric features of intersection with the Altyn Tagh fault in the western segment of the Qilian Shan (Liu et al., 2019; Jolivet et al., 2008; Shen et al., 2001; Zhang et al., 2007). These faults, including the Changma fault, the Yema-he-Daxueshan fault, and the Danhe-Nanshan fault, have been intensely active since the late Quaternary (Li et al., 2009; Meyer et al., 1998). They represent the leading edge of the Qinghai-Tibet Plateau, extend northeastward and serve as a typical tectonic transition zone (Seong et al., 2011; He et al., 2018). The left-lateral slip rates of different segments of the Altyn Tagh fault vary during the Holocene: the central and western segments west of Akesai have left-lateral slip rates of up to 17.5 ± 2 mm/year, those of the Subei-Shibaicheng segment are approximately 11 ± 3.5 mm/year (Zheng et al., 2013), those of the Shule River mouth segment decrease to approximately 4.8 ± 1 mm/year, and those of the Kuangtan Shan segment in the eastern segment are only approximately 2.2 ± 0.2 mm/year (Luo et al., 2013; Zheng et al., 2009). The transition point of the left-lateral slip rate from west to the east of the Altyn Tagh fault is located at the junction of the Subei, Shibaicheng, and Shule River Mouths in the central to eastern segments. This region is also the area where the Subei M_s 5.5 earthquake occurred. The aforementioned tectonic activity provides the seismic background for the occurrence of the Subei earthquake, highlighting the importance of determining seismogenic faults for further understanding



(Bendick et al., 2000; Mériaux et al., 2005; Gold et al., 2011; Cowgill et al., 2009).

3 Data and methods

3.1 Time series InSAR data processing

To address the shortcomings of weak surface deformation observed in small- and medium-sized earthquakes and the susceptibility to atmospheric interference, we employ a method of superimposing time-series synthetic aperture radar (SAR) phase maps (Luo et al., 2021). This method operates on the principle that interferometric SAR images contain random atmospheric errors, and by overlaying pre-seismic and post-seismic views, the atmospheric influence can be effectively mitigated, enabling the extraction of surface coseismic deformation at centimeter-level precision. Specifically, we collect 11 and 33 Sentinel-1 SAR satellite images from ascending (AT4) and descending (DT99) tracks, respectively, covering the seismic deformation zone of Surbiton. The SAR images acquired on 2023/09/19 (AT4) and 2023/10/18 (DT99) are selected as reference images, following the principle that if $N + M + 1$ (where $N + 1$ are acquired before and M after the earthquake) SAR images are available around the time of an earthquake, N interferograms excluding coseismic deformation and M interferograms including coseismic deformation can be derived using the same reference image

(Figure 2). Basic SAR interferometry data were processed using the Sentinel-1 interferometry processor (<https://sarimggeodesy.github.io/software/>). The SRTM Data Elevation Model (DEM) from NASA is utilized for alignment and terrain correction, with a resolution of 30 m (Farr et al., 2007). Interferograms are multiviewed in the azimuthal and distance directions at a ratio of four–16, and Goldstein's method is applied to filter the interferograms to enhance the signal-to-noise ratio (SNR) (Baran et al., 2003). Precision orbital data (POE) obtained from the ESA are employed to correct orbital errors, retaining only the mean orbital error. Data points with an average intercorrelation threshold greater than 0.3 are retained after eliminating orbit errors. The statistical cost network-flow algorithm for phase unwrapping (SNAPHU) is then utilized for the unwrapping process (Costantini and Rosen, 1999), followed by estimating the linear relationship between the linear slope value and elevation. Finally, the output is geocoded. Throughout the study, interferograms with significant decoherence are discarded during processing.

3.2 Relocated sequence

A more precise delineation of the aftershock sequence can be used to effectively characterize the geometry of a seismic fault (Waldhauser and Ellsworth, 2002). The currently widely utilized double-difference localization method has proven effective in obtaining more accurate locations of earthquake sources.

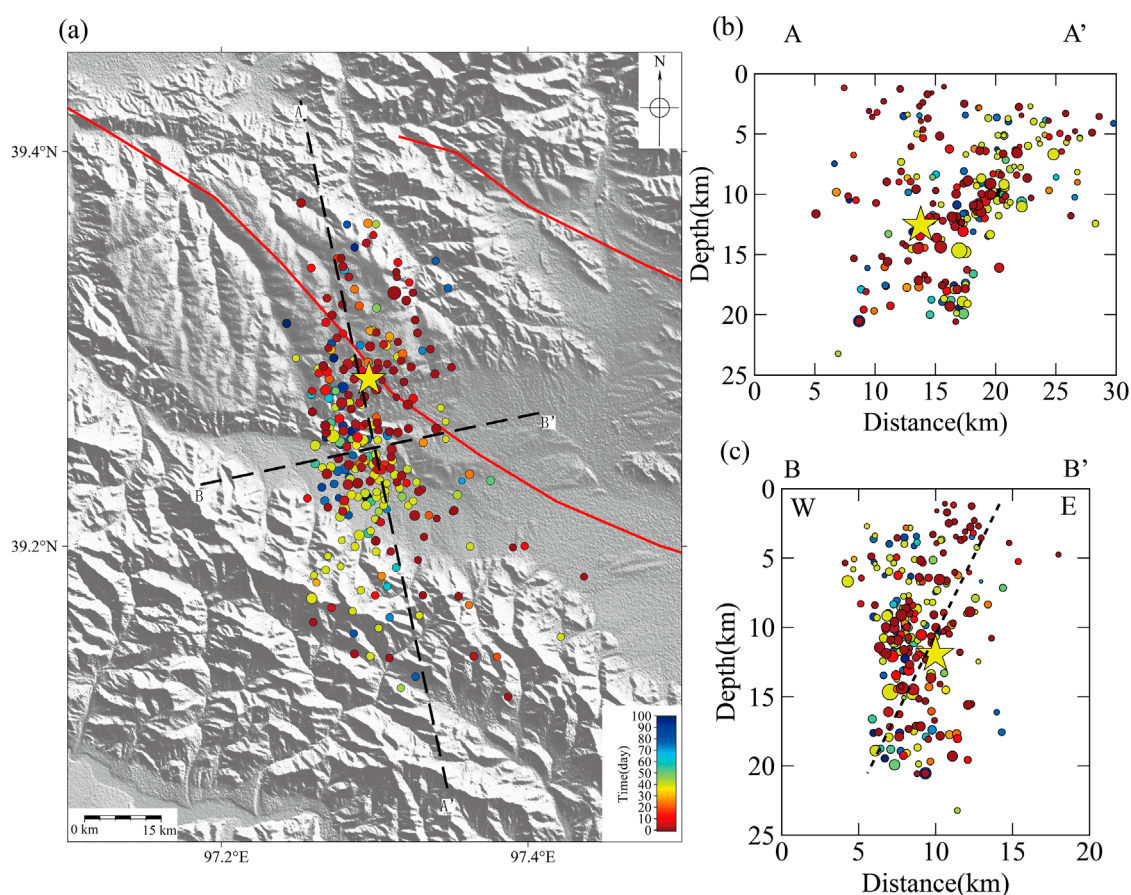


FIGURE 5

Spatial distribution of the $M_{5.5}$ Subei earthquake sequence and in 2023 after relocation. The colors represent the distribution of aftershocks in the 100 days following the occurrence of the Subi earthquake. There was a significant occurrence of aftershocks within the 100 days following the Subi earthquake. (A) Epicenter distribution. All earthquakes in the depth direction are projected onto AA' and BB' along the BB' direction. According to the results of the epicenter distribution; (B, C) Depth profiles.

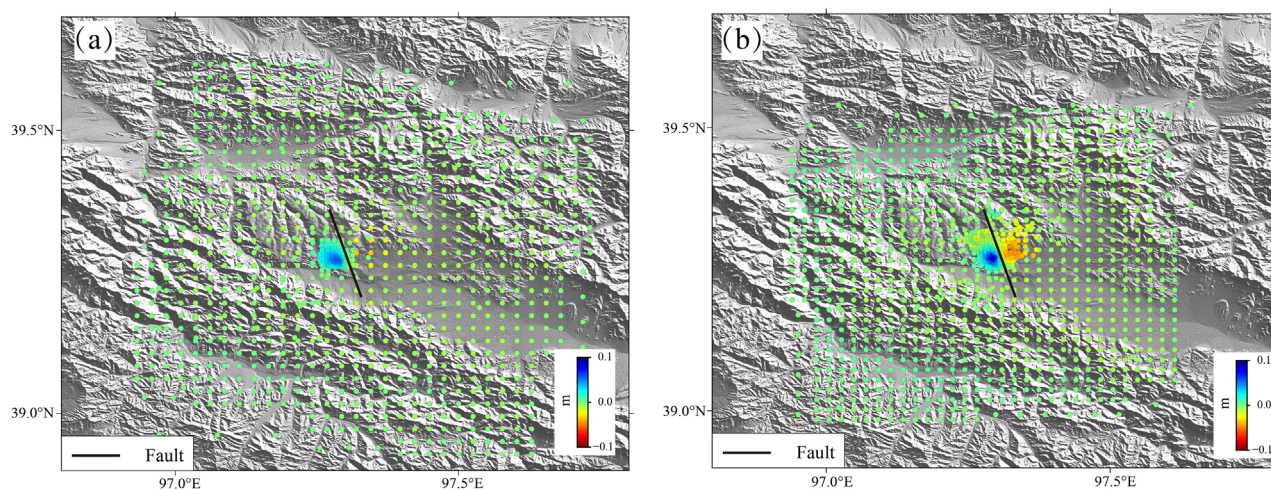


FIGURE 6

Data spatial distribution from Quadtree sampling. (A, B) show coseismic observations from ascending track and descending track. Black solid lines represent active faults model. Figures shows the downsampled data points, with blue indicating moving towards and red indicating moving away from the satellites along the radar's LOS direction.

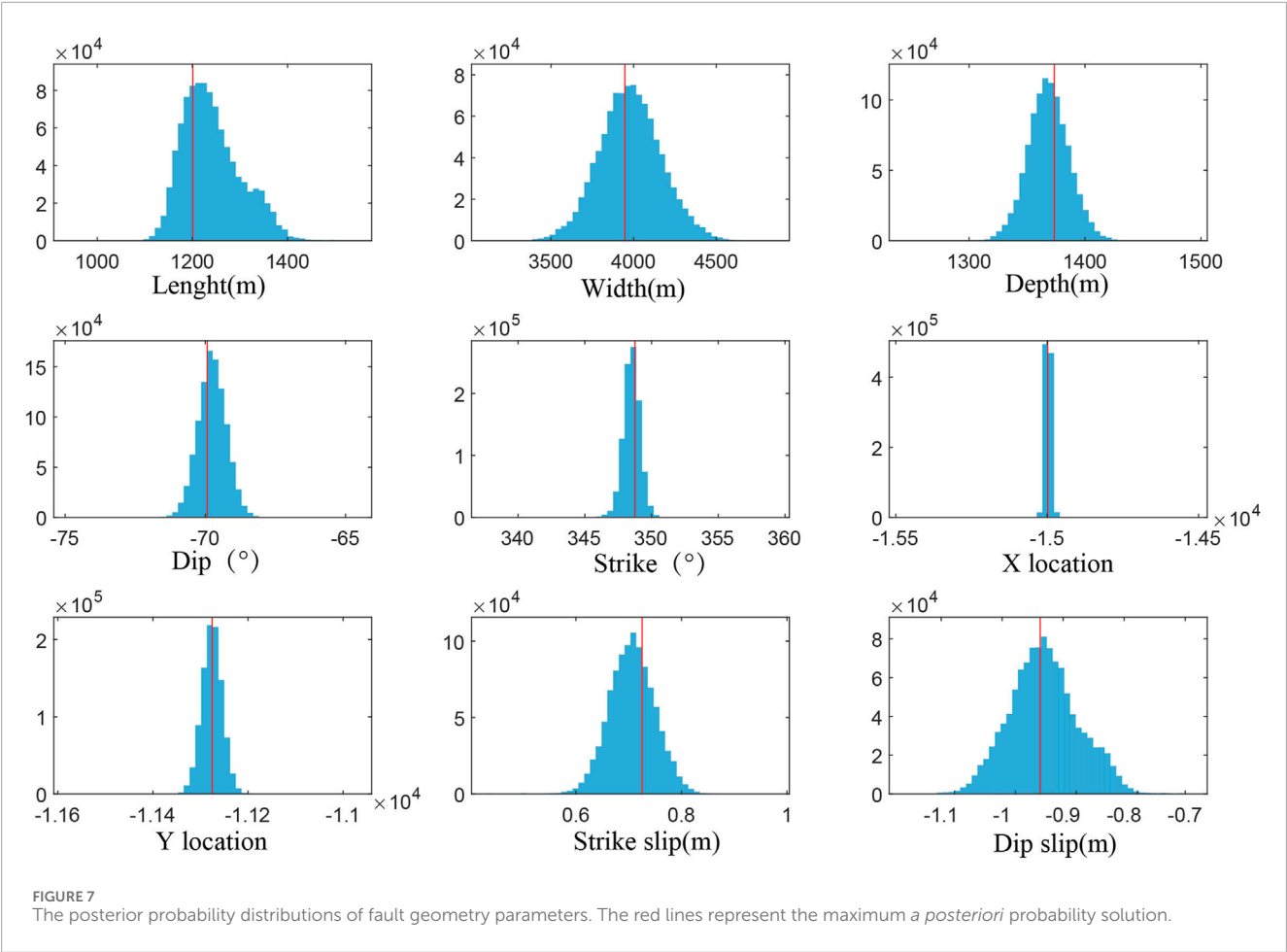


TABLE 3 Fault parameters of uniform slip inversion.

Fault Length/km	Fault width/km	Fault Depth/km	Fault Dip/(°)	Fault Strike/(°)	Strike slip/m	Dip Slip/m
12	3.9	1.38	−69	348	0.73	−0.96

At the heart of the double-difference localization method lies the pairing of seismic events based on epicentral distance and the number of phases. This approach leverages the disparity between the observed and theoretical time differences of paired seismic events relative to the same seismic station. This disparity helps mitigate errors stemming from inaccuracies in the velocity model between the source and the station. Moreover, the method employs constraints imposed on both earthquake pairing and isolated localization inversion to infer the relative positions of seismic sources. Through this process, the relative positions of the seismic sources are inverted, resulting in the precise determination of the position of the entire seismic cluster (Shelly et al., 2016).

After the M_s 5.5 earthquake in Subei on 24 October 2023, we selected 12 fixed stations with epicentral distances of approximately 200 km, as illustrated in Figure 3. This station distribution provided

better coverage of the Subei earthquake and enhanced the constraints on relocation events. We collected P-wave and S-wave data recorded at these stations for the 100 days following the mainshock. The time-dependent P-wave and S-wave data from the aforementioned stations were collected for 100 days after the main earthquake. Our study underscored the significant impact of the accuracy of the velocity model for the seismic source area on the calculation of the conjugate gradients methods (Yao et al., 2023). Therefore, the Crust1.0 crustal velocity model was chosen as the velocity model for relocation in the study area (Table 2).

HypoDD2.1b software is used with the following specific parameters: a maximum epicentral distance of 300 km, a minimum requirement of six seismic pairs, and the use of conjugate gradient methods for inversion. The initial iteration of the inversion involves five groups, each iterated 27 times. Ultimately, the precise

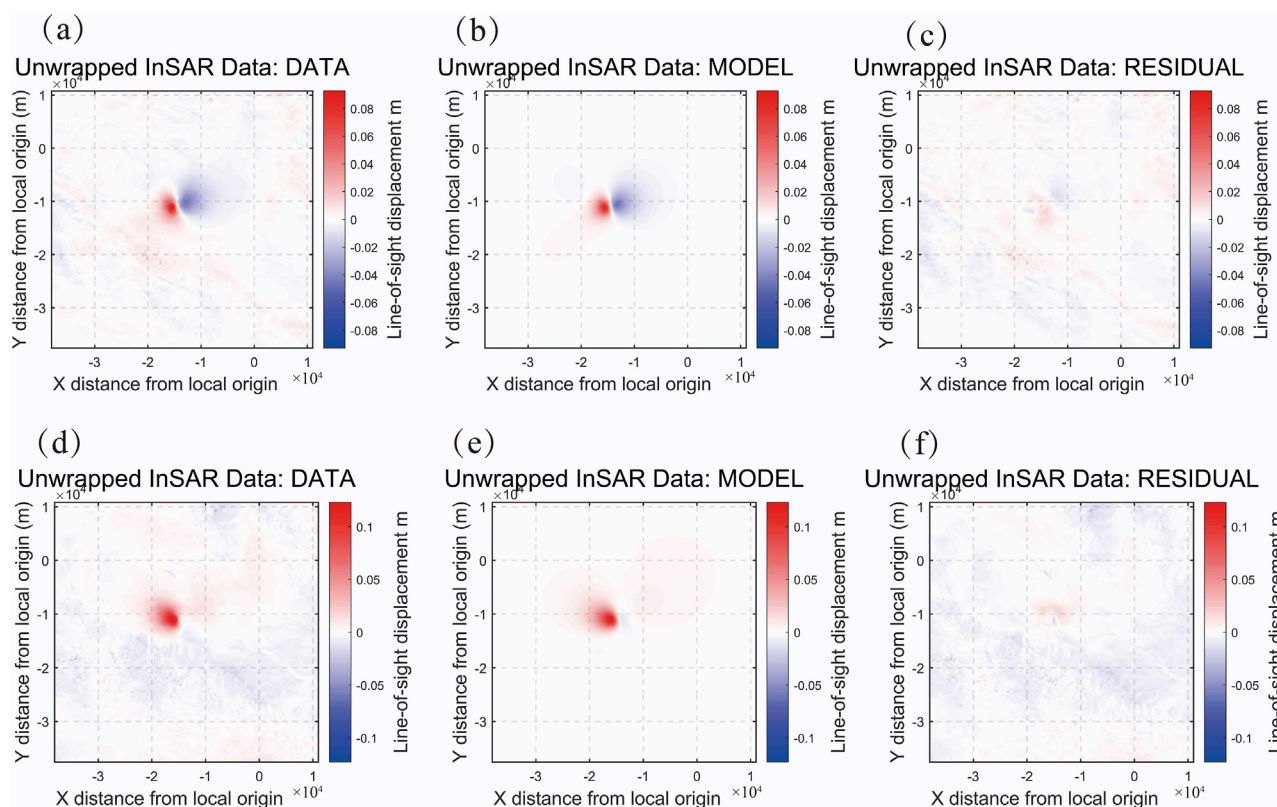


FIGURE 8

Observation data, simulation value and residual comparison result of the displacement field of the ascending and descending tracks (A–C) are the observation data, simulation value, and residual of the ascending track displacement field (D–F) are the observation data, simulation value, and residual of the descending track displacement field. The *posterior* probability distributions of fault geometry parameters. The red lines represent the maximum *a posteriori* probability solution.

relocation of the aftershock sequence following the Subei earthquake is achieved.

3.3 Fault plane fitting

Based on the principle that clustered aftershocks tend to be located near significant earthquake faults, more accurate geometric parameters of the seismic fault plane can be determined by analyzing the spatial distribution of aftershock sequences. Determining these fault plane parameters is crucial for understanding the nature and morphology of seismogenic faults. Previous researchers have used a method proposed by Wan to fit parameters of small-seismic fault planes, which has seen widespread application in characterizing faults in regions such as Huoshan and Changdao in Anhui Province (Wan et al., 2008; Xu et al., 2022). In our study, we adopt Wan's method, which assumes that aftershocks predominantly occur within the fault plane and its vicinity. This method approximates the seismic tectonic fault plane as one or multiple planes, establishing a mathematical model to solve for the fault plane parameters. We employ a combination of simulated annealing and Gaussian-Newton algorithms to calculate these parameters, enabling the determination of the geometrical parameters of the earthquake-generating faults.

3.4 Two-steps inversion strategy

Our inversion process for determining the earthquake source involved a two-steps strategy. Initially, we modeled the earthquake source as one planes with uniform slip in a homogeneous elastic half-space. This involved nonlinear processes to search for the optimum fault parameters, including size (length and width), depth, geometry (strike and dip), and slip, using the Geodetic Bayesian Inversion Software within a Bayesian framework, as described by Bagnardi and Hooper (2018).

Subsequently, we inverted the detailed fault slip distributions on the predetermined fault geometries. This was implemented using constrained least-square optimization with the steepest descent method (Wang et al., 2011).

In this paper, we use geodetic Bayesian inversion software (GBIS) to determine the fault geometry via nonlinear inversion. The GBIS software is used to determine the optimal parameters of the fault through the *a posteriori* probability density function (PDF) of the fault's geometrical parameters and the *a priori* knowledge of the observed values, and the basic idea is to use the Bayesian method to invert the measurement data to obtain the parameters that can represent the basic idea is to use the Bayesian method to invert the measurement data to obtain the PDF that can represent the fault parameters; then, the Markov

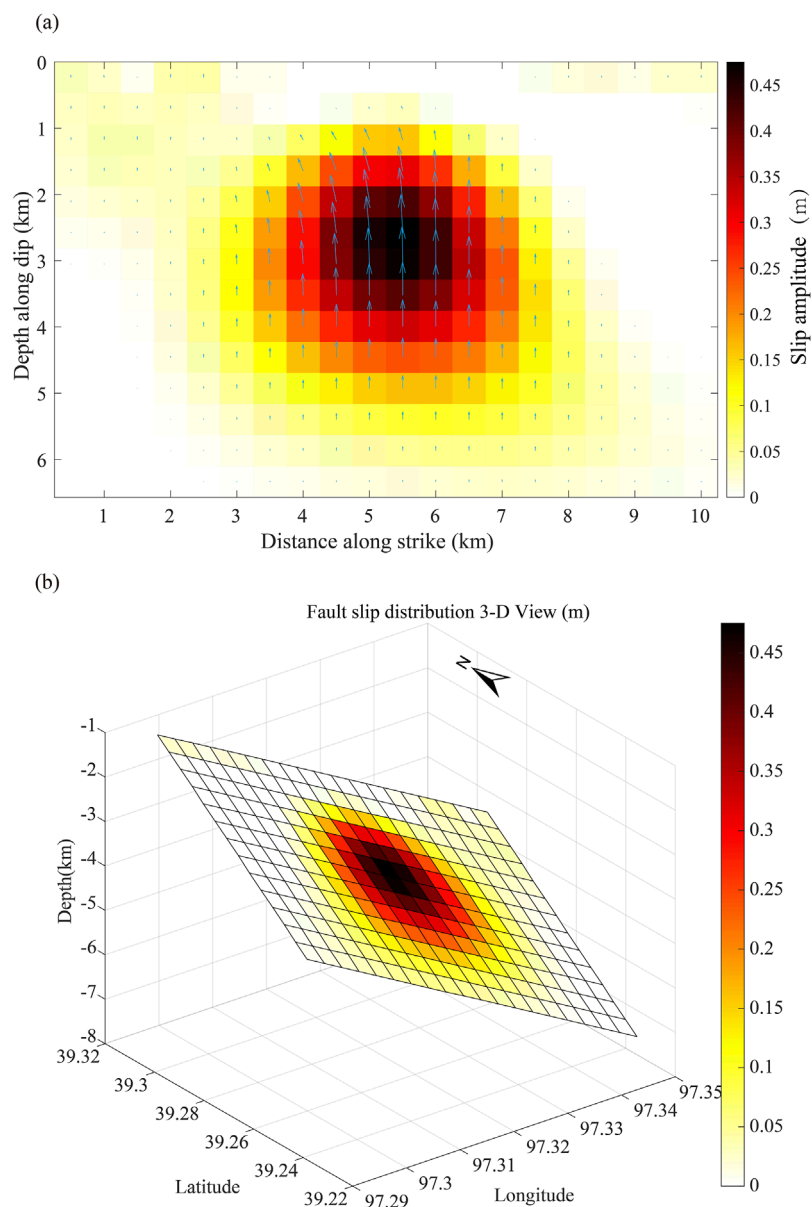


FIGURE 9

Fault slip distribution of Subei M_s 5.5 along strike. Depth profiles of slip distribution. Arrows represent the slip direction. Figure 2D. (A) planar view. The maximum slip of earthquake is 0.5 m, which occurs at 3–4 km underground. Figure (B) The 3D view of the proposed slip-distribution model with an average slip angle of 69° . The shear modulus of this region is set to 30 GPa, and the moment magnitude of the inversion is M_w 5.4.

Monte Carlo method (MCMC) is used to obtain the PDF of the parameters for downsampling, and finally, a set of optimal parameters representing the fault geometry is extracted from the *a posteriori* PDF. The *a posteriori* probabilities are represented as follows:

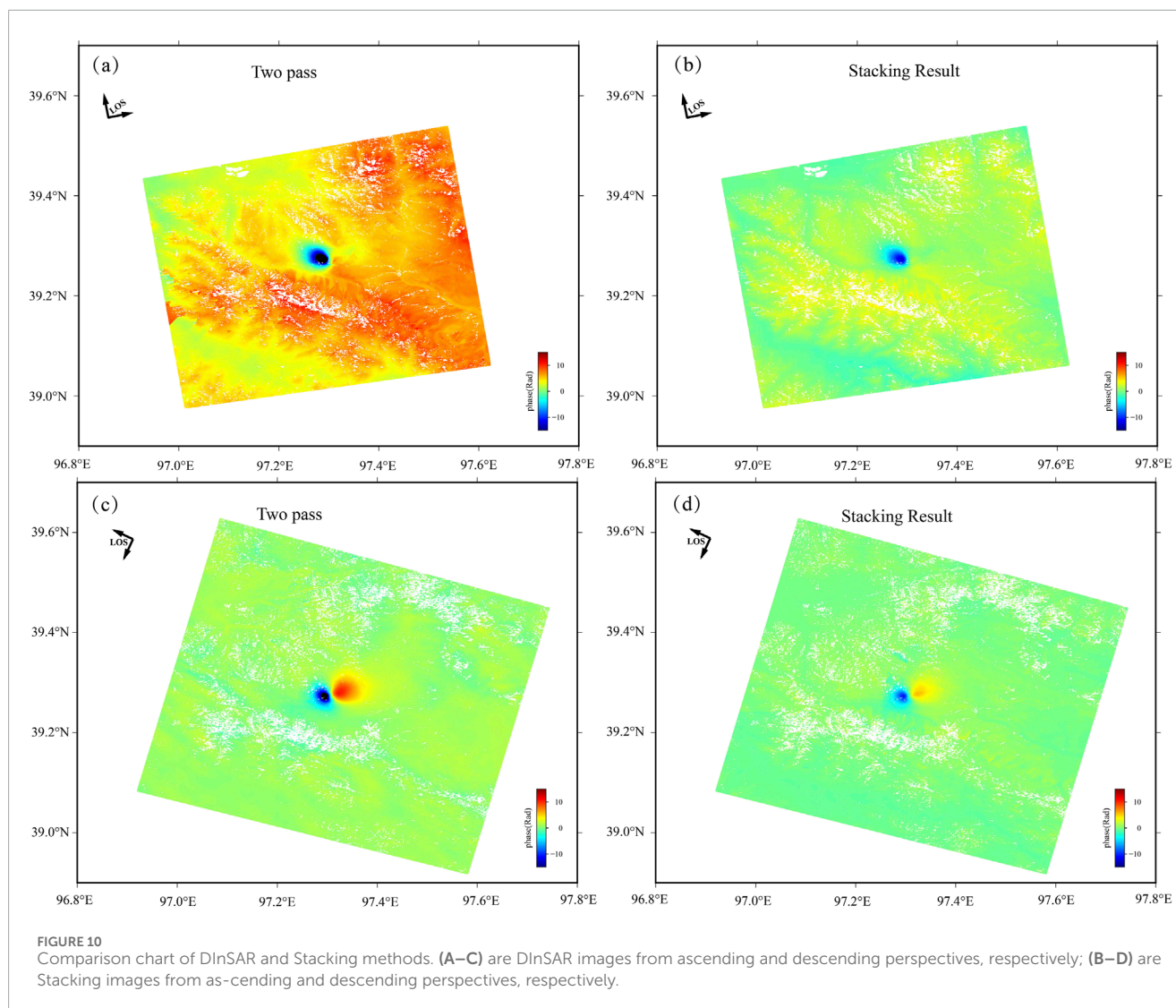
$$p(m|d) = \frac{p(d|m)p(m)}{p(d)} \quad (1)$$

where $p(d|m)$ is the likelihood function determined by the model parameters m and the observations d . In Equation 1, $p(m)$ represents the prior probability distribution of the model parameters, and $p(d)$ is an arbitrary constant. For each iteration, Green's function

G is recalculated in Equation 2, and the likelihood function is updated.

Subsequently, a detailed inversion of the fault slip distribution is performed based on an accurate fault geometry model, whose methodology is constrained to be implemented by least squares optimization and the most rapid descent method. Based on Okada's elastic halfspace dislocation model (Okada, 1985), the nonlinear function model between the fault parameters and surface deformation observations can be expressed as:

$$y = Gb + \varepsilon \quad (2)$$



4 Results

4.1 InSAR coseismic deformation

The Sentinel-1A SAR data along the Line of Sight (LOS) clearly show the whole coseismic deformation field of this earthquake (see Figure 4), and the interferograms from different tracks show relatively obvious deformation information. The coseismic deformation field caused by the Subei earthquake on both the ascending track and descending track shows that surface deformation affected an area of 15 km×15 km, and the long axis of the deformation field was approximately oriented in the northwest-southeast direction. For the ascending track, the vertical and east-west horizontal coseismic deformations cancel each other out on the LOS (Figure 4C), failing to recover the deformations of the fault downlifted block away from the satellite's LOS. The distance from the satellite is defined with a negative sign, while the proximity to the satellite is denoted with a positive sign. The maximum uplift deformation of the fault downlifted block in the LOS direction is determined to be +6.8 cm. For the descending

track, the maximum uplift deformation in the LOS direction is +6.2 cm, while the subsidence deformation is −2.9 cm. In the same region, the deformations observed in both the ascending and descending tracks exhibit opposite signs (Figure 4F). Combining the relationship between uplift and subsidence along the LOS directions of ascending and descending tracks with the operation of faults, it can be inferred that vertical deformation predominates on the Earth's surface and is accompanied by horizontal deformation.

4.2 Aftershock relocation and fault plane fitting

After relocation, we obtained the relative positions of the 141 seismic events of the M_s 5.5 earthquake sequence in Subei. To better constrain the depth of the mainshock, we used Hypoinverse2000 to determine the location of the mainshock, which was located at 97.3128°E, 39.3284°N, with an epicenter depth of 12 km, a horizontal error of 0.73 km and a vertical error of 0.95 km. Based on the solution of the seismic source mechanism given by the USGS and

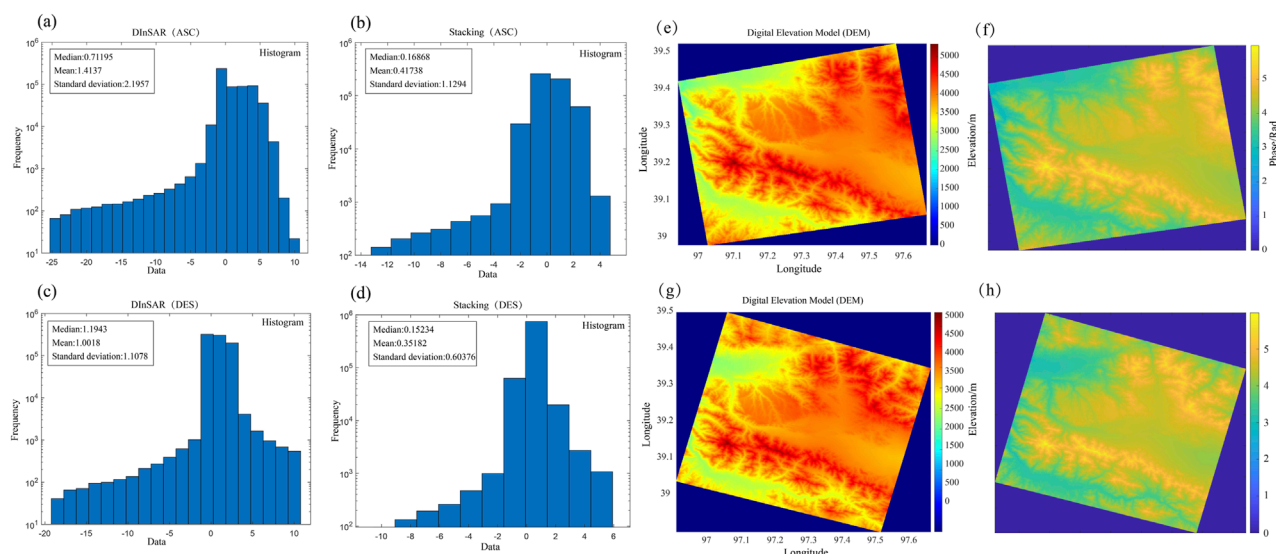


FIGURE 11

Phase unwrapping data histogram. (A–C) are DInSAR images from ascending and descending perspectives, respectively; (B–D) are Stacking images from ascending and descending perspectives, respectively; The distribution of the overall phase values in the interferograms tends to approximate a normal distribution centered around zero after the stacking process. (E–H) are DEM map of the study from ascending and descending perspectives, respectively; (F–H) are Simulated terrain phase map from ascending and descending perspectives, respectively.

combined with the InSAR coseismic surface deformation field, we set the AA' profile and the BB' profile perpendicular to it (Figure 5A). All earthquakes in the depth direction are projected onto AA' and BB' along the BB' direction. According to the results of the epicenter distribution shown in Figure 5A, aftershocks mainly occurred within 40 days after the earthquake, but there were still earthquakes occurring at the rupture location of the mainshock until 80–100 days after the earthquake, which is in line with the occurrence process of a slower release of energy from backlash-type earthquakes. The spatial distribution of aftershocks is mainly concentrated in the periphery of the mainshock, and the spatial distribution generally spreads in a nearly NNW direction, which is the basis of this paper, according to the results of the deep section projected onto the AA' and BB' sections from the BB' direction. In this paper, based on the projection of the deep section from the BB, we fit a fault section in Figure 5C, and the trend of the seismic fault is southwestward, as shown by the fitted fault line.

The geometric parameters of the fault obtained by inputting the final relocated earthquake source location into the small-seismic fault surface fitting program fit_planev2.0 are a strike of 340°, a fault dip of 65°, a fault length of 20 km, and a fault width of 10 km, which provide the basic parameters of fault modeling for the subsequent inversion of uniform-slip fault parameters.

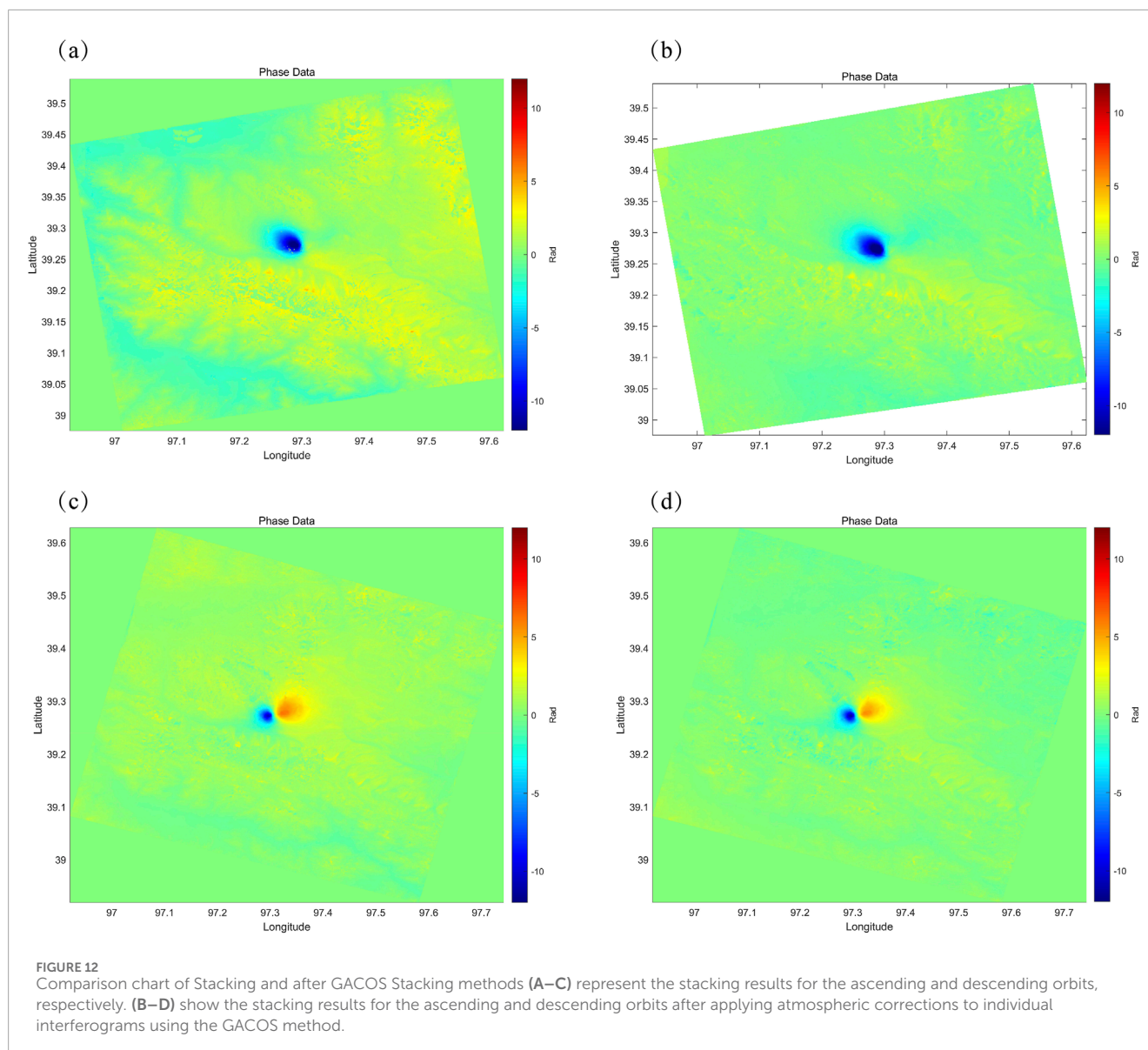
4.3 Fault geometry inversion result

To improve the inversion efficiency and retain the deformation information of the seismic source area as much as possible when using the InSAR observation dataset for the inversion of the seismic fault model, it is necessary to reduce the original InSAR data. This study combines the quadtree method and uniform

method for downsampling, and the basic information of the seismic faults obtained from the aftershock fine-location fitting is used (Wang et al., 2014). For part of the seismic source area, the quadtree downsampling method is used to downsample the dataset with the variance threshold set to 6×10^{-5} m, and for part of the farfield, uniform downsampling is used to retain the corresponding deformation information. This approach allows for effective extraction of deformation information from the source area while avoiding the sensitivity of the quadtree method to noise signals and maximizing data points in the farfield deformation area. Finally, 1353 and 1032 data vector points are obtained for the ascending and descending rails, respectively, as shown in Figure 6.

The inversion of fault geometric parameters based on the uniform slip model is carried out on the downsampled dataset using GBIS (Bagnardi and Hooper, 2018), and Figure 7 shows the histograms of the nine fault geometric parameters obtained after 10^6 iterations, while the maximum *a posteriori* probabilistic solution and the 95% credible intervals are given in the inversion results to obtain the optimal fault geometric parameters, and the results are shown in Table 3. In addition, from Figure 8, it can be seen that the residual error of the displacement field simulated by using the model parameters of the maximum *a posteriori* probabilistic solution is very small, indicating that the model parameters have a good fit to the observed data. The displacement field simulated with the maximum *a posteriori* probabilistic solution has very small residuals, indicating a high degree of fit between the model parameters and the observed data.

The inversion results of the fault slip distribution are shown in Figure 9 (Wang et al., 2013). The earthquake rupture is mainly concentrated in the depth range of 2–5 km underground, indicating that the seismic activity did not rupture to the surface, and the maximum slip of the earthquake is 0.5 m, which occurs at 3–4 km



underground, with an average slip angle of 69° . The shear modulus of this region is set to 30 GPa, and the moment magnitude of the inversion is $M_w 5.4$, which shows that the rupture of the fault is reverse faulting with strike-slip components.

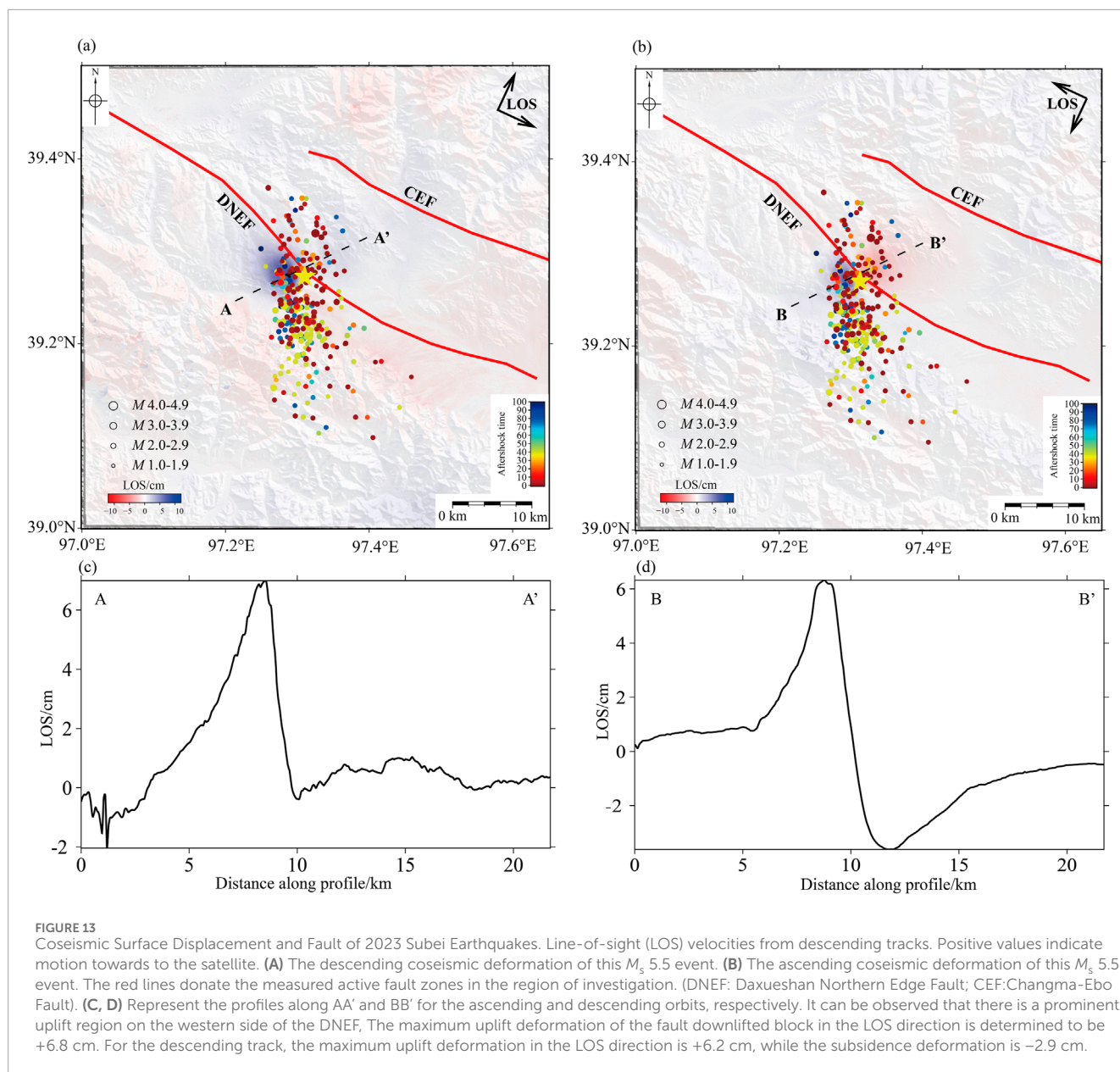
5 Discussion

5.1 Stacking atmospheric error improvement

To demonstrate the effectiveness of the adopted method in removing atmospheric delays, we recovered interferograms for the periods before and after the Subei earthquake on 24 October 2023. These periods are 19 September 2023, 12 December 2023 (AT4), 18 October 2023, and 30 October 2023 (DT99). Figure 10A presents the results of the ascending track interferograms. While the coseismic deformation signals are clearly discernible in the

recovered phase images, the atmospheric phase signals dominate the overall imagery. This predominance is primarily due to the 84-day temporal baseline of the ascending track images, which amplifies the interference errors caused by the randomness of atmospheric phases. Consequently, the single interferogram obtained outside the epicentral area cannot provide reliable measurements of the ascending-track coseismic deformation for this event. After applying the stacking method, the impact of atmospheric phase signals is significantly reduced, as shown in Figure 10B. The coseismic signals across the entire study area become much clearer. Comparing the results of the two interferograms with those of the stacking method demonstrates that the stacking method enhances the coseismic surface deformation of the Subei earthquake.

We conducted a statistical analysis of the interferograms and DInSAR data points after applying the stacking method, as shown in Figure 11. It is apparent that the distribution of the overall phase values in the interferograms tends to approximate a normal distribution centered around zero after the stacking

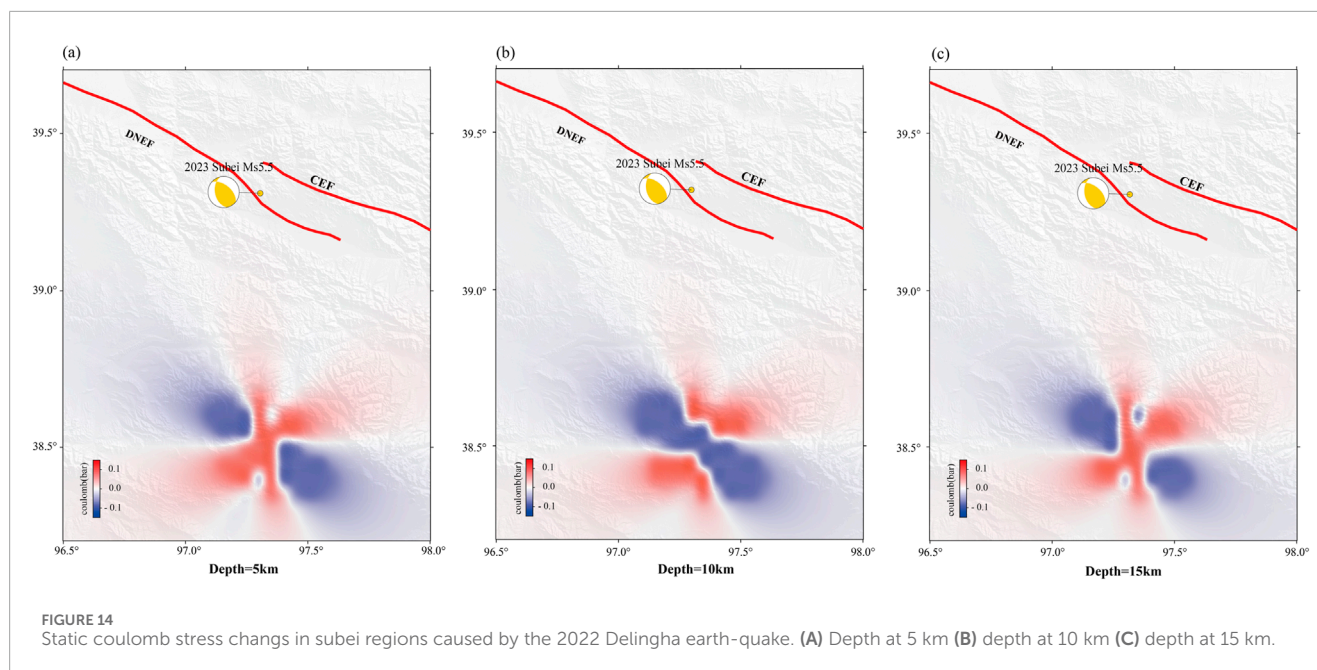


process. This is consistent with ideal InSAR observation conditions (excluding atmospheric delays and other topographic effects), where surface deformation values are expected to appear primarily near the fault zone of the earthquake rupture.

We conducted the following procedures: In order to comprehensively evaluate the efficacy of the proposed stacking method, atmospheric corrections were individually applied to the results obtained at each imaging time. Subsequently, a comparative analysis was performed by comparing these corrected results with those before and after stacking, thereby ensuring a more comprehensive assessment. Consequently, Figure 12 was generated, where Figures 12A–C represent the stacking outcomes for ascending and descending orbits respectively. Additionally, Figures 12B–D illustrate the stacking outcomes for ascending and descending orbits after applying atmospheric corrections to individual interferograms using the GACOS method. Notably, it is evident that comparing

the results with or without atmospheric corrections applied at each imaging time reveals that solely employing the stacking method does not yield significant improvements in outcomes. This implies that even when utilizing only the stacking method itself, satisfactory results can still be achieved. The interferograms for each imaging time are provided as supplementary materials to this paper.

Previous studies utilizing DInSAR technology to obtain coseismic deformation fields have inferred parameters related to the fault responsible for the earthquake based on these observations. However, it is crucial to consider that both the magnitude of the earthquake and atmospheric noise in the study area can significantly impact these results. While most case studies have concentrated on larger earthquakes, such as the Mw7.8 Kahramanmaraş earthquake in Turkey in 2023 (Barbot et al., 2023), smaller magnitude earthquakes often exhibit subtle coseismic deformation fields that are susceptible to contamination from atmospheric delays.



Furthermore, moderate to small earthquakes (e.g., $\leq M_w 5.5$) occur more frequently than larger earthquakes (e.g., $\geq M_w 6.0$). Thus, we propose a stacking method that utilizes time-series SAR images to effectively suppress atmospheric phase screens and extract weak coseismic deformations at the centimeter to sub-centimeter level.

Our study shows that InSAR stacking method for time-series analysis can be effectively applied to the extraction of coseismic deformation fields for moderate to small earthquakes, current research indicates that, generally, for earthquakes occurring in less vegetated areas, utilizing 10–30 SAR images can achieve substantial noise reduction. In highly vegetated regions, however, it is essential to carefully select interferograms with relatively high coherence to mitigate the effects of decorrelation noise, which consequently results in fewer SAR images being incorporated into our stacking method.

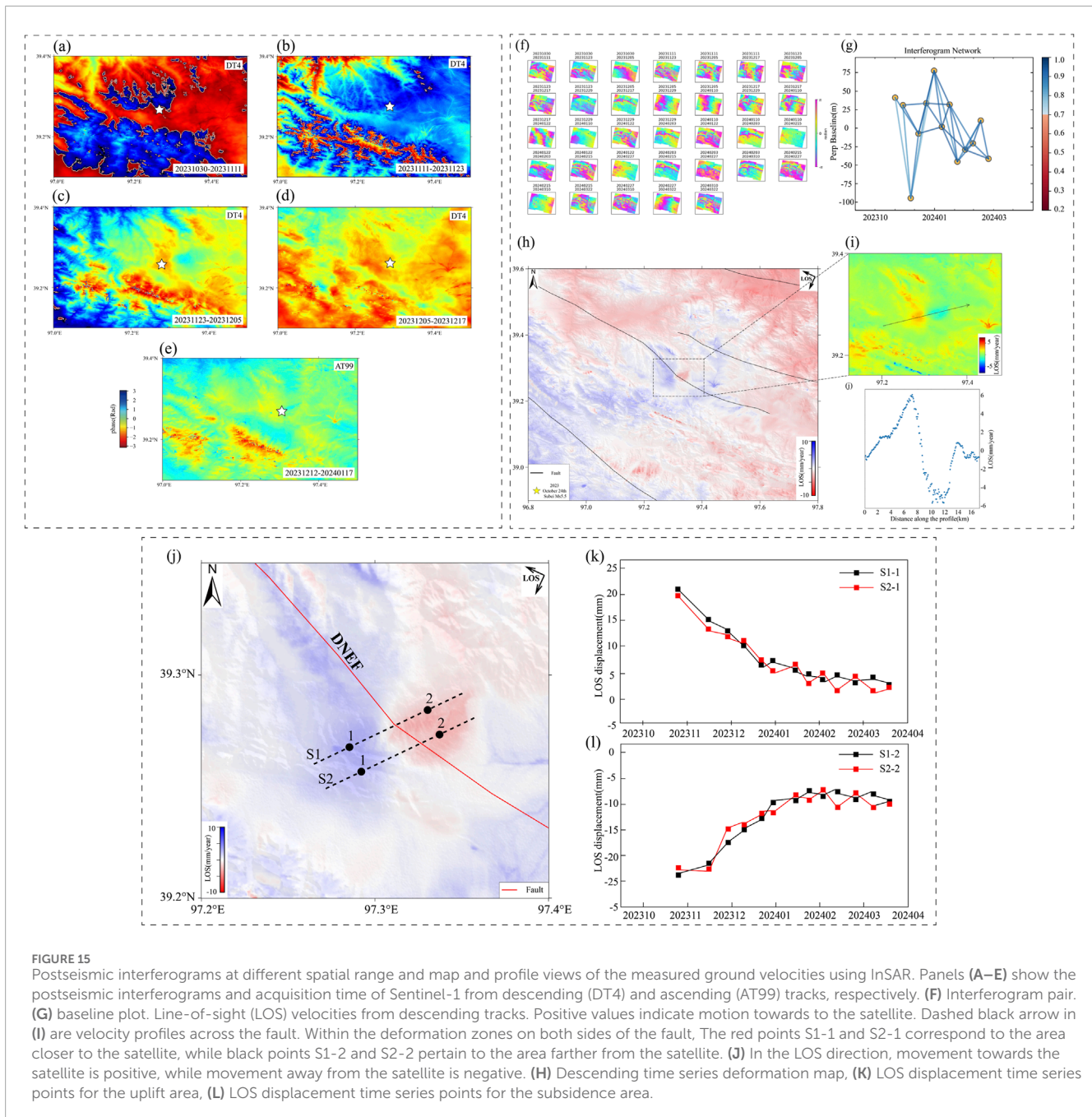
5.2 Seismogenic fault

The coseismic surface deformation observed via InSAR and the precise localization of the aftershock sequence reveal that the seismogenic fault is located at the northern margin of the Daxueshan Range (Figure 13). The western end of the northern margin fault of the Daxueshan Range intersects with the ATF. Starting from the west side of Xishuigou in Subei County to the east, it extends southeastward along the west side of the Danghe River, then turns northeastward, runs along the north side of the Yema River into the Daxueshan Range, and further extends eastward along the northern foothills of the Daxueshan Range. With an overall length of approximately 170 km, it exhibits an elongated S-shape and has a general NEE trend. Research indicates that the middle section of the Altyn Tagh Fault experiences a slip rate of 10 mm/year in the Subei region (Zhang et al., 2007), with the eastward movement being absorbed and distributed by active faults such as the Dangnan River Fault, the Shule South Mountain Fault, the Changma Fault,

and the Yema River-Daxueshan Fault (Zheng et al., 2005; Qu et al., 2005; Li et al., 2023). The fault zones existing in the study area can be collectively referred to as the Qilian Mountain Western Fault. Current research indicates that the slip rate of the ATF gradually decreases from west to east. It is generally believed that the Qilian Mountain Western Fault absorbs some of the sinistral slip component of the Altyn Tagh Fault. Based on the fault model and the inverted slip mechanism obtained in this study, the Subei earthquake is characterized as a rupture event involving reverse faulting with strike-slip components. This indicates an adjustment in the stress orientation within the seismic zone due to strike-slip displacement. The earthquake likely represents a stress release event at the transition end, reflecting the release of stress in the eastern segment of the Altyn Tagh fault or the absorption of stress through the earthquake (Rong et al., 2005). The precise localization of aftershocks shows that the epicenter is predominantly distributed on the updip side of the fault, which is consistent with the thrust faulting mechanism.

5.3 Seismic background and static Coulomb stress triggering

To further discuss the seismogenic background of the Subei earthquake, this study calculated the triggering effect of strong earthquakes occurring within a 100 km radius of the Subei earthquake. Generally, the stress state of a seismogenic region changes after a strong earthquake, which can either delay or promote the occurrence of earthquakes on nearby active faults. Numerous studies on earthquake triggering relationships indicate that interactions exist between earthquakes. When the increase in Coulomb stress reaches 0.1 bar, the seismic hazard of a fault significantly increases (Jonsson, 2002; Stein, 1999; Shan et al., 2017).



On 25 March 2022, a M_s 6.0 earthquake occurred in Delingha, Qinghai, located at 38.50°N, 97.33°E, with a depth of 10 km, approximately 89 km from the Subei earthquake epicenter. Using the fault model obtained by Li (Li et al., 2023) and the Coulomb 3.3 software package (Toda et al., 2011a; Toda et al., 2011b), we conducted a Coulomb stress analysis. During this process, Poisson's ratio was set to 0.25, and the friction coefficient was set to 0.4. The fault slip distribution of the 2022 Delingha earthquake was used as the source fault, with a strike of 170° and a dip of 90°. The fault geometry of the Subei earthquake was used as the receiver fault, and the fault parameters are listed in Table 3. The Coulomb stress changes induced by the 2022 Delingha earthquake were calculated at depths of 5 km, 10 km, and 15 km to assess their impact on the 2023 Subei earthquake. As shown in Figure 14,

the fault slip of the 2022 Delingha earthquake did not induce positive Coulomb stress changes on the seismogenic fault of the 2023 Subei earthquake at depths of 5 km, 10 km, and 15 km. This indicates that the 2022 Delingha earthquake did not significantly trigger the occurrence of the 2023 Subei earthquake.

5.4 Postseismic shallow creep and regional seismic hazard

We processed all Sentinel-1A SAR images acquired within 3 months after the 2023 Subei earthquake. Neither the ascending nor descending interferograms revealed any clear postseismic slip

signals within the coseismic rupture area. This suggests that there was no resolvable postseismic slip on the rupture fault within the noise level (Figure 15).

The postseismic interferograms indicate the absence of resolvable afterslip within the rupture area, suggesting that the accumulated strain on the unruptured surface of the reverse fault has not yet been released through postseismic afterslip (Yu et al., 2018; Langbein et al., 2006). However, the accumulated shear strain might be partially mitigated by other seismic processes, such as interseismic creep and plastic deformation (Dolan and Haravitch, 2014; Hamiel et al., 2016; Roten et al., 2017; Marchandon et al., 2021). However, the sustained sinistral slip rate on the Altyn Tagh fault is currently being absorbed by the Yemahe-Daxueshan fault in the eastern segment. In the future, the potential for earthquakes resulting from shallow reverse thrust activity in this local area should be considered.

Despite the absence of significant postseismic deformation observed in individual interferograms, the region continues to absorb stress from the eastern segment of the Altyn Tagh Fault. To further investigate, we employed a time series analysis approach, processing 6 months of interferometric data following the earthquake. Using the SBAS-InSAR method (Berardino et al., 2002), we estimated the deformation rates in the study area. Due to limited ascending pass observations, we only analyzed descending pass data. We selected the Sentinel-1 InSAR products from ASF HyP3 for the interferograms (Nicolau et al., 2021), covering the period from 30 October 2023, to 22 March 2024, which includes a total of 16 scenes and 33 pairs of HyP3 GAMMA InSAR data, as shown in Figure 15F. All selected interferometric pairs were acquired post-earthquake, indicating that none of the interferograms contain coseismic deformation information, as illustrated by the baseline plot in Figure 15G. After generating geocoded interferometric products via HyP3, we conducted deformation time series analysis in MintPy (Zhang et al., 2019). We examined the time series of points across the fault and selected two profiles, S1 and S2. Along these profiles, we selected four points on either side of the DNEF fault. We analyzed the deformation of these points over time, as shown in Figure 11J. In the line-of-sight (LOS) direction, movement towards the satellite is positive, while movement away from the satellite is negative. Within the deformation zones on both sides of the fault, we selected points S1-1 and S2-1 in the area closer to the satellite, and points S1-2 and S2-2 in the area farther from the satellite. The LOS displacement time series for each of these points was extracted, as shown in Figures 11K,L.

Within the 6-month period following the earthquake, discernible movement was still observed on both sides of the coseismic deformation zone along the DNEF fault in Figure 15H. This movement pattern is consistent with the coseismic deformation, indicating that post-earthquake, the DNEF fault continues to experience slip, manifesting at the surface as what is commonly referred to as postseismic shallow creep. This further suggests that the thrust fault near the epicenter remains under compressive stress and continues to undergo rupture. The extensive distribution of aftershocks within 100 days after the event supports this observation in Figure 5A. Therefore, while partially releasing a portion of accumulated stress near the epicenter, it can be inferred from observations of shallow creep that subei M_s 5.5 earthquake has only provided partial relief for accumulated strain. Over time, from 30 October 2023, to 31 December 2023, we observed a clear

trend of deceleration in deformation values across the fault. From January 2024 to April 2024, the deformation on both sides of the fault showed minimal variation. This indicates that within 40 days after the Subei earthquake, significant deformation occurred on both sides of the fault, primarily due to post-seismic afterslip.

Our study demonstrates that the time-series method utilizing InSAR technology is highly effective in regions along the margins of large active strike-slip faults, particularly in areas where plate boundary fault slip rates are accommodated. For example, in a region where the plate boundary fault accommodates nearly half of the left-lateral displacement between the North American and Caribbean plates, with velocities of approximately 6.8 mm/year of strike-slip and 5.7 mm/year of shortening, characteristic of transpressional motion (Calais et al., 2002; Calais et al., 2010; Calais et al., 2022a; Calais et al., 2022b; Benford et al., 2012; Corbeau et al., 2016), the method has demonstrated significant applicability.

6 Conclusion

The rapid response to the 2023 Subei earthquake was investigated in this study by utilizing ascending and descending tracks of the Sentinel-1A satellite to obtain the coseismic surface deformation field. In order to enhance the observation capabilities of InSAR for small to moderate earthquakes, a stacking method was employed. Precise locations of aftershocks within 100 days post-earthquake were determined by incorporating seismic phase arrival time data recorded by fixed seismic stations within a radius of 200 km. Furthermore, a fault model was established by integrating precise localization of earthquake sequences and fitting fault planes for minor earthquakes, allowing for discussions on the fault characteristics of the 2023 Subei earthquake. Through inversion techniques, geometric parameters and slip distribution models of the causative fault responsible for the Subei earthquake were determined, enabling exploration into its seismogenic structure and precursory background. The following conclusions were drawn.

- (1) The 2022 Subei earthquake rupture was thrust mechanism with a component of right lateral strike-slip, which did not reach the surface. The uplifted and downlifted rails showed surface deformation affecting an area of $15 \text{ km} \times 15 \text{ km}$, with the direction of the long axis of the deformation field oriented in the NNS direction. The maximum uplift deformation of the fault downlifted block in the LOS direction was determined to be 6.8 cm. For the descending track, the maximum uplift deformation in the LOS direction is 6.2 cm, while the subsidence deformation is 2.9 cm.
- (2) The earthquake rupture is mainly concentrated in the depth range of 2–5 km underground, indicating that the fault rupture did not reach surface, and the maximum slip of the earthquake is 0.5 m, which occurs at 3–4 km underground, with an average slip angle of 69° . It is preliminarily determined that the causative fault of the 2023 Subei earthquake was the Daxueshan Northern Edge Fault.
- (3) The Coulomb stress changes induced by the 2022 Delingha earthquake were calculated using the causative fault of the 2023 Subei earthquake as the receiver fault. The results indicate that the fault slip from the 2022 Delingha earthquake at

depths of 5 km, 10 km, and 15 km did not generate positive Coulomb stress changes on the seismogenic fault of the 2023 Subei earthquake. This suggests that the 2022 earthquake did not significantly facilitate the occurrence of the 2023 earthquake. The seismogenic structure of the 2023 earthquake is attributed to the northern margin fault of the Daxueshan range, representing a seismic event resulting from the release of accumulated stress due to sustained sinistral slip on the eastern segment of the Altyn Tagh Fault.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

YY: Conceptualization, Data curation, Formal Analysis, Methodology, Writing—original draft. ZZ: Formal Analysis, Funding acquisition, Writing—review and editing. ZeL: Software, Validation, Writing—review and editing. ZiL: Formal Analysis, Visualization, Writing—review and editing. GW: Resources, Visualization, Writing—review and editing. JJ: Conceptualization, Formal Analysis, Writing—review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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