Fault-slip distribution characteristics and seismogenic tectonics of the Mw 7.0 earthquake on 23 January 2024 in Wushi County, Xinjiang, revealed by InSAR

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Fault-slip distribution characteristics and seismogenic tectonics of the $M_w$ 7.0 earthquake on 23 January 2024 in Wushi County, Xinjiang, revealed by InSAR

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Abstract: Satellite data of the Sentinel-1 of a $M_w$ 7.0 earthquake on 23 January 2024, in Wushi County, Xinjiang, was used to obtain the interferometric synthetic aperture radar (InSAR) co-seismic deformation field by inverting the kinematic parameters of the seismogenic fault and the fine slip distribution characteristics. Finally, Coulomb stress characteristics and regional tectonic background research results were synthesised to assess the seismic hazard around the Kepingtage fold-and-thrust belt. The deformation field generated had a long axis-oriented NEE occurring in the Kepingtage fold-and-thrust belt. The line-of-sight uplift deformation promoted the uplift of the Kepingtage fold-and-thrust belt. The seismogenic fault was assumed to be the Maidan Fault exposed in the piedmont of the Kepingtage fold-and-thrust belt. The depth of the main earthquake rupture was $0\sim(16 \pm 3)$ km, controlled by the NEE-oriented extrusion stress. The main rupture led to the dislocation of the horizontal slip layer in the Palaeozoic sedimentary cover of the Kepingtage fold-and-thrust belt. Calculations of static Coulomb stress changes indicated a reduced risk of future earthquakes in the Maidan Fault, while the potential rupture risk of the Wensu North Fault needs to be considered. The InSAR deformation field of the aftershocks reflected that the deformation field of the two strong 5.7-magnitude aftershocks was 15 km south of the mainshock. The aftershock's seismogenic fault was a thrust fault in the middle of the Wushi Basin. This was a branch fault of the main shock; i.e., a forward spreading fault developed at the front end under the continuous thrust of the Maidan Fault.

Keywords: 2024 Wushi earthquake; InSAR; fault-slip distribution; seismogenic tectonics
1. Introduction

According to China Earthquake Networks Centre (CENC), a Mw7.0 earthquake occurred in Wushi County, Aksu Region, Xinjiang (41.26°N, 78.63°E) 02:09 on 23 January 2024. The depth of the epicentre was 22 km, and the maximum intensity of the earthquake reached IX. At 8:00 a.m. on 26 January 2024, 4,216 aftershocks (2 ≤ Ms ≤ 5.7) were recorded. Three people were killed and six injured. Houses within Wushi County were damaged to varying degrees (including collapsed houses, collapsed yard walls, and some cracked walls). From focal mechanism solutions of the 2024 Wushi earthquake provided by the CENC, Global Centroid Moment Tensor (GCMT) of Harvard University, and United States Geological Survey (USGS), this earthquake was a typical reverse thrust event that occurred in the Kepingtage fold-and-thrust belt. Another strong seismic event occurred in Wushi after the M 6.2 earthquake in 2005; detailed information is presented in Table 1.

Table 1 Source parameters of the 2024 Wushi earthquake

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Source</th>
<th>Longitude/East (°)</th>
<th>Latitude/North (°)</th>
<th>D/km</th>
<th>Section I(°)</th>
<th>Section II(°)</th>
<th>Earthquake magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wushi Earthquake, Xinjiang</td>
<td>GCMT</td>
<td>78.57</td>
<td>41.19</td>
<td>14</td>
<td>236</td>
<td>48</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>USGS</td>
<td>78.649</td>
<td>41.269</td>
<td>13</td>
<td>235</td>
<td>45</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>CENC</td>
<td>78.63</td>
<td>41.26</td>
<td>19</td>
<td>252</td>
<td>75</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>GFZ</td>
<td>78.70</td>
<td>41.27</td>
<td>15</td>
<td>251</td>
<td>38</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>IPGP</td>
<td>78.59</td>
<td>41.29</td>
<td>22</td>
<td>234</td>
<td>50</td>
<td>51</td>
</tr>
<tr>
<td>This study</td>
<td></td>
<td>78.63</td>
<td>41.25</td>
<td>9.19</td>
<td>239</td>
<td>45</td>
<td>35.59</td>
</tr>
</tbody>
</table>

Note: GCMT: Global Centroid Moment Tensor; USGS: United States Geological Survey; CENC: China Earthquake Networks Centre; GFZ: German Research Centre for Geosciences; IPGP: Institut de physique du globe de Paris.

The earthquake occurred in the Tianshan seismic zone. The Tianshan seismic belt is in Central Asia, with the Pamir Plateau and the Tarim Basin in the south and the Kazakh...
Plateau and the Junggar Basin in the north. Since the Cenozoic Era, due to the intense collision of the Indian plate with the Eurasian plate and the continuous extrusion, the Tianshan seismic zone has become the largest regenerative orogenic zone within the Eurasian continent. Crustal movement is manifested as nearly north-south extrusion deformation. It is one of the strongest seismic activity areas in China. According to the records, 17 earthquakes of 6 magnitude or above have occurred within 200 km from the epicentre of the Wushi $M_w 7.0$ earthquake since 1900. The largest was the $M_w 6.8$ earthquake in Bachu, Xinjiang, on April 14, 1961. The most recent one was the $M_w 6.4$ earthquake in Gashi, Xinjiang, on 19 January 2020 (Li et al., 2021; Wang et al., 2023). However, most studies were relatively old, and the studies of the seismogenic structures in the Tianshan seismic zone were insufficient. Therefore, there was a lack of in-depth understanding of the Tianshan seismic zone's deep geometric characteristics and fault behaviour. This became an obstacle to further understanding the orogenic movement and assessing future earthquake risks. Considering that the 2024 Wushi earthquake was an intense earthquake event in the region, the study of its seismogenic mechanism is valuable for understanding the active tectonic features of the Tianshan seismic zone as well as the kinematic characteristics, geometry and seismogenic structures of the seismogenic faults in the Kepingtage fold-and-thrust belt.

In the early 1990s, Massonnet D first used interferometric synthetic aperture radar (InSAR) technology to acquire the co-seismic deformation field of the Landers earthquake in the United States. After 30 years of development, the modern space geodetic techniques represented by InSAR and GNSS have been widely used in the application and study of seismic crustal deformation (Johnson et al., 1996; Delouis et al., 2002; Elliott et al., 2016; Daout et al., 2019; Saber et al., 2023). In this study, we used the ascending and descending orbits Sentinel-1A SAR data (TOPS mode) from the European Space Agency (ESA) to rapidly reconstruct the InSAR co-seismic deformation field of the $M_w 7.0$ earthquake on 23 January 2024 in Wushi County, Xinjiang. Based on the elastic half-space dislocation model (Okada), the geometric parameters of the seismogenic faults and the distribution of co-seismic sliding were inverted. Then, the deformation field characteristics, the nature of the fault motion, and the seismogenic structure of this earthquake were analysed. Based on the results of co-seismic sliding, a static Coulomb rupture criterion was established to assess the future seismic hazard of the region, which can provide a basis for regional earthquake

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prevention and mitigation work.

**Fig. 1** Tectonic setting of the 2024 $M_{w}$7.1 Wushi earthquake
The grey lines in Fig. 1a show the secondary block boundaries (Zhan et al., 2005), the black arrows indicate the interseismic GPS velocity field relative to the Eurasian plate (Wang & Shen, 2019), and the blue frame shows the range of Figure 1(b); the red lines in Fig. 1b indicate the active faults in China (Qu et al., 2008), the red focal spheres are the focal mechanism solutions for the Wushi earthquake given by USGS and GCMT, the blue focal spheres are the focal mechanism solutions for the M > 6 earthquakes since 1970 given by USGS, the white frames show the coverage areas of ESA's Sentinel-1A ascending and descending orbits, and the blue frame shows the range of Fig. 1c; the red lines in Fig. 1c indicate the active faults.

2. Geotectonic Background and Seismic Hazards
The studies on the GPS velocity field indicated that the present-day motion of the Tianshan Mountains is characterised by nearly north-south extrusion. The crustal shortening rate was ~19–20 mm/a, close to half of the average rate of extrusion subduction between the Indian and Eurasian plates (~46 mm/a) (Sun et al., 2022). The Wushi $M_w$7.0 earthquake occurred at the collision front of the two tectonic units of the Southern Tianshan and the Tarim Basin. The seismogenic background of this earthquake was the Maidan Fault, the root fault of the Kepingtage fold-and-thrust belt. The Maidan Fault is a complex fracture zone composed of several secondary faults with a general strike of NEE, forming an imbricated tectonic structure and extending deep. They together formed a fold-and-thrust system. Previous geophysics, tectonic geology, and seismology observations have shown that the fault zone has been active since the late Quaternary and is still subjected to continuous compressive tectonic deformation. The vertical slip rate was ~0.67–0.75 mm/a, and the horizontal crustal shortening rate caused by fault activity was 1.15 mm/a, which provides the tectonic conditions for moderate to strong earthquakes (Wu et al., 2014; Jia et al., 2016). In particular, the continuous uplift of the South Tianshan and the relative subsidence of the Tarim Basin led to the rupture of rocks at the tectonic boundaries, resulting in an area of strong seismic activity (Xu et al., 2000; Zhang et al., 2019). More importantly, most of the strong seismic activity occurring in the southwestern Tianshan was centred in the Maidan Fault, the Kepingtage fold-and-thrust belt, the southwestern Tianshan piedmont concealed fault, and the Atushi anticline (Xu et al., 2006; Qiao et al., 2007; Tu et al., 2008; Fig. 1).

The Kepingtage fold-and-thrust belt is between the southwestern Tianshan (southern
margin) and the Tarim basin (northern margin). It is a reverse fault-fold belt formed in the late Cenozoic period in the Tianshan orogenic belt. It consists of several fold-front faults, inverted anticline folds, and piggyback basins or valleys near EW and NEE directions (Yang et al., 2006; Jia et al., 2019; Zhang et al., 2021). The epicentre of the current Wushi earthquake identified by USGS, GCMT, and CENC was in the Piedmont thrust fault at the northeastern edge of the Kepingtage fold-and-thrust belt (Fig. 1). Meanwhile, previous studies suggested that the Kepingtage fold-and-thrust belt has a thin-skinned structure (Zhang, 2023), and that Precambrian evaporites at the northwestern margin of the Tarim basin are the main slip layer. This viewpoint was contradicted by a series of earthquakes occurring in the region with the source depths in the range of 13–33 km (the seismogenic depth of the thin-skinned tectonic model was in the reverse fault of the upper crust at a depth of 5–10 km, which was prone to sliding). Therefore, the 2024 Wushi $M_w$7.0 earthquake study has great significance for clarifying the seismogenic structure and seismogenic mechanism of the Kepingtage fold-and-thrust belt and the future seismic risk of the Maidan fault area.

3. Construction and Analysis of InSAR Co-Seismic Deformation Field

The revisit period of the Sentinel-1 satellite is 12 days, which provided suitable SAR data for our study of the Wushi earthquake on 23 January 2024. In this paper, images from the ascending orbit T56 and the descending orbit T34 covering the seismic area were selected for InSAR interferometric processing (Werner et al., 2000) of the pre-earthquake (13 and 14 January 2024) and post-earthquake (25 and 36 January 2024) images. The data parameters are shown in Table 2. ALOS DEM (30 × 30 m resolution) was used to remove phase errors caused by the terrain phase (Farr et al., 2007). Multi-look processing with a range look of 6 and an azimuth look of 1 was applied to the SAR images during interferometric processing to suppress the noise of the interferometric phase. The interferometric phase filtering was carried out by the Goldstein filtering method (Goldstein et al., 1998), which can improve the clarity of interferometric fringes and reduce the incoherent noise caused by spatial or temporal baselines. The minimum cost flow algorithm was used for phase unwrapping (Werner et al., 2002) to solve the $2\pi$ ambiguity problem. Finally, the GCP (Ground Control Point) were selected for orbit refinement and re-flattening to correct the satellite orbit and phase offset. The deformation data were geo-coded and projected into the WGS-84 geographic coordinate system to obtain the line-of-sight (LOS) co-seismic
deformation field of the Wushi earthquake, as shown in Fig. 2.

Table 2 Differential interferometric image parameters for ascending and descending orbits

<table>
<thead>
<tr>
<th>Orbit direction (orbit number)</th>
<th>Imaging date</th>
<th>Polarisati on mode</th>
<th>Azimuth of line of sight α(°)</th>
<th>Incidence angle of line of sight θ(°)</th>
<th>Spatial baseline (m)</th>
<th>Time baseline (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asc (T56)</td>
<td>14-01-20</td>
<td>26-01-20</td>
<td>VV</td>
<td>-13.695</td>
<td>34.152</td>
<td>-20.995</td>
</tr>
<tr>
<td>Des (T34)</td>
<td>13-01-20</td>
<td>25-01-20</td>
<td>VV</td>
<td>-166.364</td>
<td>33.943</td>
<td>-7.420</td>
</tr>
</tbody>
</table>

The ascending and descending orbits InSAR co-seismic deformation fields (Fig. 2) show that the co-seismic deformation fields generated by this earthquake were in the northeastern edge of the Kepingtage fold-and-thrust belt. The long axes of the deformation fields were in the NE direction, indicating that the strike of the seismogenic fault was in the NE direction. The LOS deformation field of ascending and descending orbits had two prominent deformation regions with the same deformation symbol. Among them, the maximum uplift displacement was ~0.77 m in the ascending orbit and the maximum uplift displacement was ~0.39 m in the descending orbit, indicating that the seismogenic fault's motion was a reverse thrust. Meanwhile, the deformation field of the ascending and descending orbits showed asymmetric distribution, and the LOS deformation of the north plate was larger than that of the south plate.
Fig. 2 InSAR co-seismic deformation field of the 2024 $M_w$7.0 Wushi earthquake

(a) ascending orbit interference fringes; (b) ascending orbit interferometric displacement field; (c) descending orbit interference fringes; (d) descending orbit interferometric displacement field. The red focal spheres represent the focal mechanism solutions of the Wushi earthquake determined by USGS and GCMT. Black thrust fault traces are identified as active fault systems in the study area. An interference fringe colour circumference represents a displacement of 50 mm in the LOS direction. The blue lines indicate the profile lines of AA', BB', CC', and DD', and the results of the profile measurements are shown in Fig. 3. MDF: Maidan Fault, WSNF: Wensu North Fault.

Fig. 3 Ascending and descending orbits co-seismic deformation profile measurement results of 2024 $M_w$7.0 Wushi earthquake

Four cross-deformation field profiles of AA', BB', CC', and DD' were selected in the InSAR deformation field, and the profiles are plotted in Fig. 3. The co-seismic
deformation field of ascending and descending orbits exhibited mainly lifting
deformation from the four deformation profiles. The geometrical deformation of the
deformation curves was consistent with the deformation characteristics of the thrust
earthquake.

4. Inversion of Co-Seismic Source Sliding Distribution

In this study, the reconstructed InSAR co-seismic deformation field with ascending
and descending orbits was used as a constraint to study and analyse the fault
parameters and the sliding mechanism of the 2024 Wushi earthquake using the Okada
model. After acquiring the InSAR interferograms, the downsampling process was
performed to reduce the far-field noise and improve the inversion efficiency. The
number of ascending orbit points obtained by the uniform downsampling method was
4,902, and the number of descending orbit points was 3,293 (Lohman et al., 2005).
The focal mechanisms given by different research organisations for teleseismic body
wave inversion were the same (Table 1). In this paper, we referred to the focal
mechanisms of the first set of nodal planes released by the USGS and the GCMT and
the previous research results on the geometry and kinematic properties of the Maidan
fault to determine a seismogenic fault trace on the reconstructed InSAR co-seismic
deformation field in the NEE direction. With the rupture of the south-dipping thrust
fault (the model fit was significantly reduced after the fault trace was set as
north-dipping thrust fault), the initial geometric parameters of the seismogenic fault
were constructed as follows: the fault length of 95 km (78.1°E–78.9°E), the fault
width of 28 km, the strike of 239°, the dip direction of NW, the dip angle of 0°–50°,
the slip angle of 0°–100°. The simulated annealing algorithm was used to test the fault
model with different dip angles, and the optimal fault dip angle was finally
determined to be 45°. Finally, the fault plane was divided into 672 sub-faults of 2 km
× 2 km for the inversion of co-seismic slip distribution. The fault inversion in this
paper used the SDM program (Wang et al., 2013). Many scholars have described its
basic principles (Tu et al., 2016; Li et al., 2021; Yu et al., 2023), which this paper will
not repeat.

The fine slip model of the fault obtained with InSAR deformation field inversion
shows (Fig. 4) that the dip angle was ~45° and the centroid depth was ~9.19 km for
the seismogenic fault plane. These two parameters coincided with those of the slip
layer at the base of the sedimentary layer within the Kepingtage fold belt. Therefore,
we hypothesised that the rupture surface of the 2024 $M_w$7.0 Wushi earthquake may correspond to the weak slip surface at the base of the sedimentary layer (Allen et al., 1999). This earthquake directly reflected the stress produced by the compression between the Tarim Basin and the Tianshan Mountains and its concentrated release. However, as the Tarim block has subducted below the southwestern Tianshan Mountains, it cannot be ruled out whether the deep fault caused sliding. Meanwhile, the fault rupture surface was ~40 km long and ~20 km wide. The rupture of the eastern fault extended to the surface, and the sliding was mainly concentrated in the depth range of 9–20 km below ground. The maximum sliding was ~2.4 m, the average sliding angle was 35.59°, and the moment magnitude was $M_w$7.04 (Fig. 5). The results were basically in line with the results of USGS and GCMT.

Fig. 4 Three-dimensional co-seismic sliding distribution model
From the residual distribution of the fault-slip model inverted from InSAR ascending and descending orbits data (Fig. 6), the simulated deformation field's distribution characteristics and deformation levels were consistent with those of the observed deformation field. The root mean square errors of the fitting residuals of ascending and descending orbits data were 2 and 2.5 mm, respectively. The fitting degree of the data model reached 98.49%. This indicated that the fault-slip distribution model established in this paper for the Wushi earthquake had certain reliability and rationality.

Fig. 6 Plots of observed, simulated and residual values obtained from the InSAR ascending and descending orbits constrained inversion

5. Regional Seismic Risk Assessment

5.1 Co-Seismic Coulomb Stress Changes

To a certain extent, the accumulation of underground stresses can lead to sudden misalignments in the crustal rock layers, which can produce earthquakes. At the same
time, the occurrence of earthquakes will lead to changes in the stress field of the region and stimulate changes in fault activity in neighbouring regions. The Coulomb stress is widely used in studies of the triggering relationship between strong earthquakes and aftershocks, as well as in the assessment of regional seismic hazards to judge the change of fault activity under different stress perturbations (Wang et al., 2012; Shan et al., 2017; Liu et al., 2022).

This paper took the determined south-dipping fault-slip distribution model as the source fault and the seismogenic fault of this earthquake as the receiving fault. Using Coulomb 3.3 software developed by Toda et al., the static Coulomb stress disturbance in adjacent areas caused by the co-seismic rupture of the 2024 Wushi earthquake was calculated (Toda S et al., 2005). In this paper, the static Coulomb stress changes generated by the Wushi earthquake at depths of 5, 10, 15, and 20 km were calculated at an interval of 5 km. The equivalent static friction coefficient was assumed to be 0.4, the shear modulus was $3 \times 1,010$, and the Poisson’s coefficient was 0.25. Fig. 7 shows the variation of $\Delta$CFS caused by the 2024 Wushi earthquake in the four depth ranges.

It can be found that the unloading of $\Delta$CFS occurred in the north-south region of the near-field of the seismogenic fault within the depth range of 10 km, while the loading of $\Delta$CFS occurred in the north-south region of the seismogenic fault in the deeper depth range of 10 km. This phenomenon was related to the shallow rupture depth (9–20 km) of the Wushi earthquake. Due to the large magnitude of this earthquake, the $\Delta$CFS generated by the mainshock extended up to 100 km beyond the epicentre and gradually decayed beyond 100 km. From the macroscopic distribution of $\Delta$CFS, the eastern section of the Maidan fault was in the state of stress unloading within 50 km east of the epicentre, and its $\Delta$CFS was less than 0. The western section of the Maidan fault had a $\Delta$CFS value greater than 0 in the depth range of over 10 km west of the epicentre, and the largest $\Delta$CFS reached 0.03 Mpa. Considering that the aftershocks of the Wushi earthquake further released the stress loading, the danger of the Maidan fault having larger earthquakes in the future may be reduced. Meanwhile, the Coulomb stress changes at different depths showed that the Wushi earthquake produced noticeable Coulomb stress loading on the Wensu North Fault. Its seismic risk may increase and require special attention.
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**Fig. 7** Static Coulomb stress changes in the neighbouring regions due to the 2024 Wushi earthquake

MDF: Maidan Fracture, WSNF: Wensu North Fracture, PQF: Piqiang Fracture, KPF: Keping Fracture

5.2 Regional strain rate field analysis based on current GPS

In order to elucidate the regional tectonic dynamics underlying the Ushi earthquake, we employed the strain calculation method proposed by Wang et al. (2020) and Shen et al. (2015) based on GPS horizontal velocity field data. Consequently, we calculated the surface strain rate field and maximum shear strain rate field in the Keping area (Fig. 8a, b). The results of the strain rate analysis within the earthquake zone indicate an overall negative surface strain rate, suggesting predominant compressive
deformation with weak tensile deformation. This observation aligns with our
determination that this Wushi earthquake is primarily associated with compressive
thrust movement along its seismogenic fault. Notably, significant compressive strain
characteristics were observed in proximity to the earthquake area along faults such as
Maidan-Shayram fault, Piqiang fault, and Keping fault. The Wushi earthquake
occurred in a high-value region of compressive strain between the southern trunk of
Tianshan and Tarim Basin where there was a substantial change in strain rate gradient.
Principal strain rates reveal evident NS-trending extrusion between Kepingtagh
foreland thrbelt and Kuqa foreland thrust belt, indicating an overall clockwise rotation
pattern resulting from continuous northward push of Indian plate following collision
with Eurasian plate (Sobel et al., 1997; Yin et al., 1998). Furthermore, examination of
maximum shear strain rates (Fig. 8b) reveals relatively low values within the
earthquake area consistent with limited strike-slip component exhibited by this Wushi
earthquake occurrence near eastern section of Maidan fault where high stress
accumulation suggests potential seismic hazard.

Figure 8. (a) Surface and principal strain rates. (b) Maximum shear and
principal strain
6. Discussion

This paper’s fault-slip distribution model of the 2024 $M_w$ 7.0 Wushi earthquake using InSAR inversion was consistent with the focal mechanisms obtained from the teleseismic body waves (USGS, GCMT and GFZ). It indicated that the 2024 $M_w$ 7.0 Wushi earthquake was a sliding rupture event with a low dip angle within the sedimentary layer. The rupture depth range was $\sim 0$–(16 ± 3) km. Meanwhile, the characteristics of InSAR co-seismic interference fringes revealed the uplifting effect of this earthquake on the Kepingtage fold-and-thrust belt. We believed that this earthquake directly manifested the horizontal extension of the Kepingtage fold-and-thrust belt into the Tarim Basin and the rapid vertical uplift. It should be noted that the Sentinel-1A data provided a temporal resolution of 12 days, and the earliest post-earthquake observation images used in this paper were 2 days after the earthquake. So, the deformation features corresponding to the InSAR interference fringes may reflect the deformation caused by aftershocks after the main earthquake (Barnhart et al., 2013). This paper further used the Sentinel-1A ascending and descending orbit data from ESA to obtain the aftershock InSAR deformation field from 25 January to 7 February after the 2024 Wushi earthquake (Fig. 8), which showed an 8 km long NE-trending incoherent region. It was consistent with the displacement of the surface rupture zone obtained by the field geological expedition of the China Earthquake Administration's on-site research team. The maximum line-of-sight displacements of the ascending and descending orbits InSAR deformation field of the aftershock were $\sim 42$ and 37 cm, respectively. The minimum line-of-sight displacements were $\sim 16$ and 13 cm, respectively (Fig. 8c and d). The deformation area was located $\sim 15$ km south of the $M_w$ 7.0 mainshock. The long axes of the ascending and descending orbits in InSAR deformation areas were NEE-oriented. The displacements of the north plate of the ascending orbit were larger than those of the south plate. The seismogenic fault is inclined to NW. The displacements of the south plate of the ascending orbit were larger than those of the south plate. The seismogenic fault tended SE. We speculated that the seismogenic fault of the aftershock was a thrust fault located in the middle of the Wushi Basin, which was a branch fault of the main seismogenic fault of the main shock; i.e., a forward spreading fault developed at the front end under the continuous thrust of the Maidan Fault. The strong 5.7-magnitude aftershocks on January 24 and 29 might have occurred in this forward-spreading fault. It was noteworthy that, in addition to the aftershock
deformation revealed by the largest deformation region, there was another deformation zone with complex deformation characteristics on the southeast side of the ascending orbit deformation field. This deformation zone revealed the post-earthquake activity of another fault, which may correspond to at least one strong aftershock. In this paper, the reconstructed ascending and descending orbits InSAR co-seismic deformation field from Sentinel-1A clearly showed that the co-seismic surface deformation caused by the 2024 $M_w$7.0 Wushi earthquake was distributed in the Kepingtage fold-and-thrust belt. On this basis, the Okada model inversion yielded a fault strike of 239°, a south dip of 45°, and an average slip angle of 35.59°. A south-dipping thrust and a small strike-slip movement characterised the fault rupture. This was consistent with the geometric kinematic properties of the Kepingtage fold-and-thrust belt and its root Maidan Fault obtained by Wu et al. (2014), Jia et al. (2015), Jia (2019), Wang et al. (2020) through field surveys, geodesy, remote sensing image interpretation, exploration and excavation, and seismic tomography imaging techniques. Therefore, this paper concluded that the seismogenic tectonics of the Wushi earthquake was the Maidan thrust fault within the Kepingtage fold-and-thrust belt.
Fig. 8 InSAR co-seismic deformation field of the strong aftershock of the 2024 Mw7.0 Wushi earthquake (a) ascending orbit interference fringes; (b) ascending orbit interferometric displacement field; (c) descending orbit interference fringes; (d) descending orbit interferometric displacement field. The black focal spheres represent the focal mechanism solutions of some strong aftershocks in the Wushi earthquake. The black thrust fault traces are the identified active fault systems in the study area. An interference fringe colour circumference represents a displacement of 25 mm in the LOS direction. MDF: Maidan Fault, WSNF: Wensu North Fault

7. Conclusion

On 23 January 2024, a $M_w$7.0 earthquake in Wushi County, Xinjiang, occurred in the Kepingtage fold-and-thrust belt, where the Tianshan Mountains and the Tarim Basin squeezed each other. In this paper, the D-InSAR technique was deployed to construct this earthquake's InSAR co-seismic deformation field using the ascending and descending orbits data of Sentinel-1A IW from ESA. On this basis, the InSAR deformation field was used to calculate the fault geometric parameters and co-seismic slip distribution characteristics of this earthquake and to discuss the seismogenic structure characteristics of this earthquake and its surrounding seismic hazards. The conclusions are as follows:

(1) The seismogenic fault of the $M_w$7.0 Wushi earthquake was the Maidan fault, which was a thrust fault. The LOS deformations of the north plate were significantly larger than those of the south plate, which showed that the seismogenic fault had a south-dipping nature. The depth of the main shock was $\sim$0–(16 ± 3) km, controlled by the NEE extrusion stress. The main rupture area was most likely the horizontal slip layer in the Paleozoic sedimentary cover of the Kepingtage fold belt. Only the rupture of thin-skinned tectonics can produce an earthquake of $M_w < 6.4$ (Zhang et al., 2021). Thus, we hypothesised that the current strong 7-magnitude earthquake in Wushi was caused by the cascade rupture of the contact surface (thick-skinned tectonics) between the Piedmont thrust fold belt (thin-skinned tectonics) and the Tarim block under the triangular wedge of the Tianshan Mountains.

(2) The rupture of the $M_w$7.0 Wushi earthquake produced a maximum uplift displacement of $\sim$0.76 m in the LOS direction of the ascending orbit. The uplift deformations of the ascending and descending orbits were more significant than the subsidence deformations, reflecting that surface deformation produced a significant uplift of the folds in the leading edge of the Kepingtage fold belt.
(3) From the distribution of macroscopic changes in ΔCFS, the risk of future strong earthquakes in the Maidan Fault may be reduced. Meanwhile, earthquakes produced noticeable Coulomb stress loading effects on the Wensu North Fault. We need to focus on the potential risk of rupture in this fault.

(4) The InSAR deformation field of the aftershock reflected that the deformation field of the $M_w 5.7$ strong aftershock that occurred on January 24 and 29 was located ~15 km south of the mainshock. It was inferred that the seismogenic fault of the aftershock was a thrust fault located in the middle of the Wushi Basin, which was a branch fault of the seismogenic fault of the main shock; i.e., a forward spreading fault developed at the front end under the continuous thrust of the Maidan Fault.

Authors' contributions


Statements & Declarations

The authors declare that they have no know competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Competing Interests
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References


Jia, Q. C. (2016). Late Quaternary activity characteristics and seismic hazard analysis of the Aheqi section of the Maidan Fault. China Earthquake Administration Lanzhou Institute of Seismology


Research: Solid Earth, 102(B3), 5043-5063
Wang, J., J, Xu, C., J, Shen, W, B. (2012). The Coseismic Coulomb Stress Changes Induced by the 2010 Mw 6.9 Yushu Earthquake, China and Its Implication to Earthquake Hazards. Geomatics and Information Science of Wuhan University, 37(10), 1207-1211


Zhang, Y., F. (2021). The geometric and kinematics of the foreland active thrust faults: insight from geodetic deformation observations. Institute of Geology, China Earthquake Administration