

From subsurface damage to surface instability: Integrating InSAR, UAV and microseismic observations of deep longwall mining beneath thick loess

Jiangtao Qiu

qiujiangtao@smac.ac.cn

The Second Monitoring and Application Center, China Earthquake Administration

Xinxin Yin

Earthquake Administration of Gansu Province

Lingyun Ji

The Second Monitoring and Application Center, China Earthquake Administration

Liangyu Zhu

The Second Monitoring and Application Center, China Earthquake Administration

Hongbin Cheng

The Second Monitoring and Application Center, China Earthquake Administration

Zongpan Bian

The Second Monitoring and Application Center, China Earthquake Administration

Haibo Wang

State Key Laboratory of Cryospheric Science and Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences

Research Article

Keywords: InSAR, Mining-induced ground instability, Multi-source Earth observation, Microseismicity, UAV photogrammetry, Surface deformation

Posted Date: September 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10876025/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

From subsurface damage to surface instability: Integrating InSAR, UAV and microseismic observations of deep longwall mining beneath thick loess

Authors

Jiangtao Qiu^{1*}, Xinxin Yin², Lingyun Ji¹, Liangyu Zhu¹, Hongbin Cheng¹, Zongpan Bian¹, Haibo Wang³

Affiliations

1 The Second Monitoring and Application Center, China Earthquake Administration, Xi'an 710054, China

2 Earthquake Administration of Gansu Province, Lanzhou 730000, China

3 State Key Laboratory of Cryospheric Science and Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China

*Corresponding author: qiujiangtao@smac.ac.cn (<https://orcid.org/0000-0001-5733-187X>)

Abstract

Mining-induced ground instability involves coupled deformation and damage processes across surface and subsurface domains, which are difficult to characterize using a single Earth observation technique. This study integrates time-series Sentinel-1 InSAR, UAV photogrammetry, and continuous microseismic observations to investigate progressive ground instability associated with deep longwall mining beneath a thick loess cover in northwestern China. InSAR observations reveal the spatial and temporal evolution of mining-induced deformation, while UAV surveys characterize surface fissures and localized geomorphological failure within zones of concentrated deformation.

Microseismic observations provide complementary information on subsurface damage accumulation and episodic high-energy failure. Cross-correlation analysis indicates that cumulative Benioff strain precedes accelerated surface deformation by approximately 17 days ($R = 0.47$), providing an observational link between subsurface damage accumulation and subsequent surface deformation acceleration. The two largest microseismic events produce nearly synchronous responses in subsurface seismicity and surface deformation, indicating distinct temporal responses associated with progressive damage accumulation and major structural failure. Integrating the three observation sources reveals a four-stage progression from damage initiation and interaction to deformation localization and surface failure. The results demonstrate the value of multi-source Earth observations for resolving the spatiotemporal evolution of mining-induced ground instability and provide an integrated observational framework for geohazard monitoring in deeply mined, loess-covered regions.

Keywords

InSAR; Mining-induced ground instability; Multi-source Earth observation; Microseismicity; UAV photogrammetry; Surface deformation

1. Introduction

Mining-induced ground deformation and surface instability are important anthropogenic geohazards in underground coal-mining regions. The progressive response of the overburden to longwall extraction may evolve from localized subsurface damage and distributed deformation to spatially concentrated surface displacement, ground fissuring, and localized failure. This evolution is particularly complex in areas where thick unconsolidated deposits overlie the mining-induced deformation zone, because the mechanical response of the overburden and its surface expression may occur at different spatial and temporal scales. Identifying how subsurface damage evolves into observable surface instability is therefore important for understanding mining-induced ground hazards and for developing effective monitoring strategies.

Remote sensing and geophysical observations provide complementary opportunities for characterizing this evolution. Time-series interferometric synthetic aperture radar (InSAR) has become an effective technique for monitoring mining-induced ground deformation over large spatial areas and with millimetric deformation sensitivity. InSAR can continuously characterize the spatial distribution, temporal evolution, and kinematic acceleration of surface deformation, thereby providing valuable information on the development and migration of mining-induced subsidence. In particular, deformation velocity, acceleration, and spatial deformation gradients can provide information beyond cumulative displacement and may help identify zones where deformation becomes increasingly localized. However, InSAR primarily observes the surface manifestation of subsurface processes. Cumulative surface deformation alone does not directly reveal the development of internal damage or the dynamic processes responsible for subsequent deformation acceleration and surface failure.

UAV photogrammetry and microseismic monitoring can provide complementary observations at different spatial and physical scales. High-resolution UAV surveys enable detailed characterization of surface morphology, including ground fissures, localized deformation features, and small-scale failure structures that may not be adequately resolved by satellite observations. Microseismic monitoring, in contrast, provides indirect information on subsurface fracture and damage activity through the spatial and temporal distribution of seismic events and their associated energy release. Parameters such as event frequency, magnitude, cumulative seismic energy, and Benioff strain can therefore provide complementary indicators of subsurface damage evolution. Integrating satellite-scale deformation, UAV-scale surface morphology, and subsurface microseismicity offers an opportunity to link different manifestations of mining-induced instability that cannot be fully resolved by any single observation technique.

Despite these advances, an important challenge remains in establishing the spatiotemporal relationship between subsurface damage and surface deformation.

Previous studies have demonstrated the effectiveness of InSAR for mapping mining-induced deformation and the potential of UAV and geophysical observations for characterizing localized surface or subsurface responses. However, the progressive transition from distributed subsurface damage to localized surface deformation and eventual surface failure is difficult to resolve when these observations are analyzed independently. In particular, three aspects require further investigation. First, it remains necessary to determine how initially separated or spatially distributed deformation zones evolve and interact before becoming localized areas of accelerated deformation. Second, the relationship between surface failure features and kinematic indicators such as deformation acceleration and spatial deformation gradients requires further characterization. Third, the temporal relationship between subsurface damage accumulation and subsequent surface deformation acceleration remains insufficiently constrained, particularly in deep mining environments where surface and subsurface responses may exhibit distinct timescales.

These issues are particularly relevant to deep longwall mining beneath thick loess deposits. The relatively weak and heterogeneous nature of loess and the thickness of the unconsolidated cover can influence the transmission of mining-induced deformation from the subsurface to the ground surface. Under such conditions, the surface response may not simply follow cumulative subsidence but may involve progressive deformation localization, interaction between neighboring subsidence zones, and subsequent development of ground fissures or localized failure. Resolving these processes requires observations that capture both the broad spatial evolution of surface deformation and the localized surface and subsurface responses associated with instability.

In this study, we investigate progressive ground instability induced by deep longwall mining beneath a thick loess cover in northwestern China by integrating time-series Sentinel-1 InSAR, UAV photogrammetry, and continuous microseismic observations. The study is designed around three complementary objectives. First, we characterize the spatial and temporal evolution of mining-induced surface deformation using time-series InSAR, with particular emphasis on deformation velocity, acceleration, and spatial gradients. Second, we use high-resolution UAV observations to identify and characterize localized surface fissures and failure features and examine their spatial relationship with InSAR-derived deformation patterns. Third, we quantify the temporal coupling between subsurface microseismic damage and surface deformation evolution using cumulative Benioff strain and cross-correlation analysis. Through the integration of these complementary observations, we aim to establish an observation-based understanding of the transition from subsurface damage accumulation to surface deformation localization and failure.

The results provide three main contributions. First, the integration of InSAR, UAV, and microseismic observations resolves mining-induced ground instability across

complementary spatial and physical domains, allowing regional deformation, localized surface failure, and subsurface damage to be examined within a common framework. Second, the temporal coupling analysis identifies an approximately 17-day observational lead of cumulative Benioff strain relative to accelerated surface deformation, providing quantitative evidence for a lagged relationship between subsurface damage accumulation and surface deformation response. Third, the combined observations reveal a progressive four-stage evolution from damage initiation and interaction to deformation localization and surface failure. These findings demonstrate the value of multi-source Earth observations for resolving the spatiotemporal evolution of mining-induced ground instability and provide an integrated observational framework for geohazard monitoring in deeply mined, loess-covered regions.

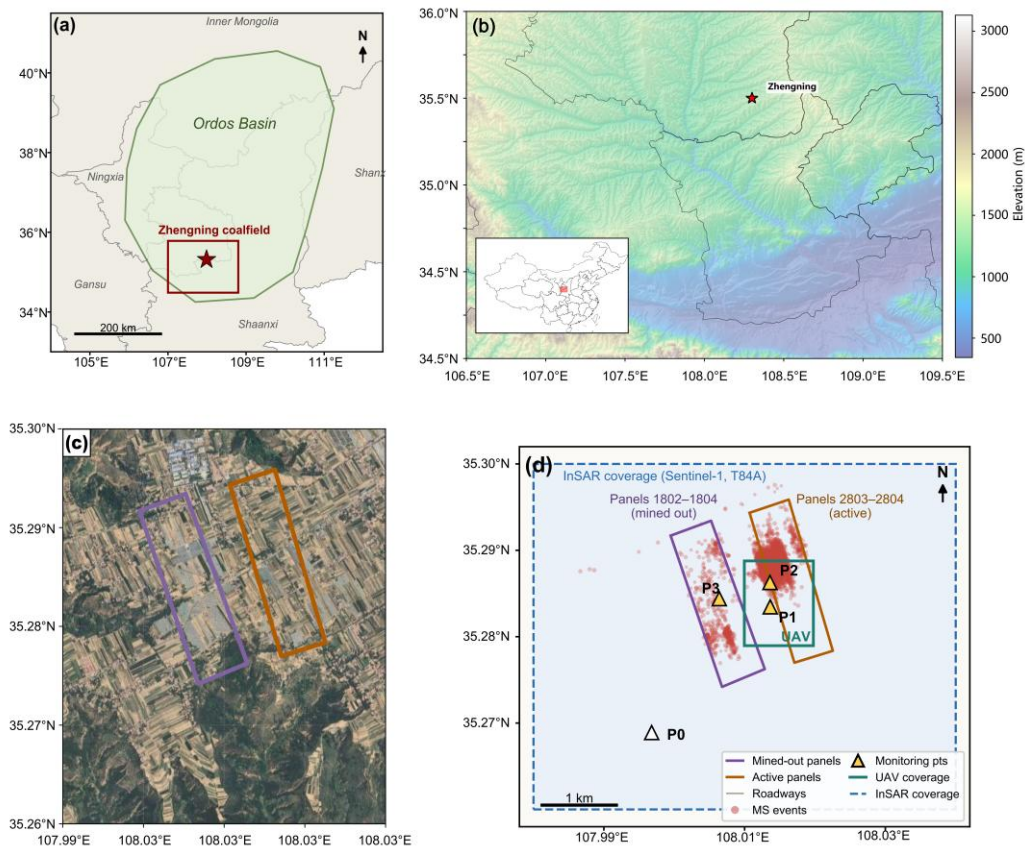


Fig. 1. Study area and monitoring configuration in the Zhengning coalfield, Ordos Basin, China.

(a) Geographic location of the Zhengning coalfield within the Ordos Basin. (b) Regional topography surrounding the study area. (c) High-resolution satellite image showing the locations of longwall panels. Panels 1802 – 1804 had already been extracted before the monitoring

period, whereas Panels 2803 – 2804 were actively mined. (d) Layout of the integrated monitoring system, including Sentinel-1 InSAR coverage, UAV survey extent, representative InSAR monitoring points (P0 – P3), underground microseismic events, and longwall panel boundaries. P0 is located outside the mining influence zone and serves as the deformation reference. LOS, line of sight; UAV, unmanned aerial vehicle; DOM, digital orthomosaic; P95, 95th percentile; POD, probability of detection; FAR, false-alarm rate; NSGA-II, non-dominated sorting genetic algorithm II.

2. Study Area and Data

2.1 Study area

The study area is located in Zhengning County, eastern Gansu Province, China, on the southwestern margin of the Ordos Basin (Fig. 1). This region belongs to the central Chinese Loess Plateau, where thick Quaternary loess deposits extensively mantle the landscape and create one of the world's most representative loess-covered coal mining environments. Elevations range from approximately 920 to 1300 m above sea level, forming a gently undulating loess tableland dissected by gullies (Zhao, et al.,2022) . Sparse vegetation cover and relatively simple land use provide favourable conditions for satellite-based deformation monitoring.

Unlike conventional coal mining districts developed in exposed bedrock terrains, the Zhengning mining area is characterized by the combination of deep underground extraction, thick competent bedrock, and an exceptionally thick loess cover (Qin, et al.,2021), resulting in a distinctive deformation response to underground excavation. The Quaternary loess reaches an average thickness of approximately 200 m and exhibits high porosity, weak cementation, abundant vertical joints, and strong collapsibility. These engineering geological characteristics promote localized deformation, tensile cracking, and sudden structural collapse once mining-induced disturbances propagate into the loess layer (Xu, et al.,2007). Consequently, deformation evolution in this region differs substantially from that in shallow-bedrock mining areas, where surface subsidence is generally more continuous and directly controlled by overburden movement.

The stratigraphic succession consists of the Upper Triassic Yanchang Formation, the Lower Jurassic Fuxian Formation, the Middle Jurassic Yan'an Formation, the Middle Jurassic Zhiluo and Anding formations, the Lower Cretaceous Zhidan Group, and the overlying Neogene – Quaternary deposits. Coal extraction is concentrated within the Middle Jurassic Yan'an Formation, which contains three economically recoverable seams (Nos. 2, 5, and 8). The present study focuses on the No. 8 coal seam, buried at depths of approximately 600 – 1000 m and mined using fully mechanized longwall top-coal caving. The immediate roof consists predominantly of thick sandstone, producing a hard-

roof mining environment that favors extensive overburden fracture development before large-scale surface deformation becomes apparent (Cheng, 2026; Qin, et al.,2021).

Two adjacent longwall panel groups constitute the principal mining area investigated in this study. The previously mined 1802 – 1803 panels have already formed an extensive goaf, whereas the neighbouring 2803 – 2804 panels were undergoing intensive extraction during the monitoring period. The coexistence of active and abandoned panels generated continuous stress redistribution and strong mechanical interactions between adjacent mined-out areas, creating favourable conditions for progressive deformation accumulation and subsequent instability transition. Field investigations conducted during the study period documented numerous ground fissures, collapse pits, graben-like subsidence structures, and localized scarps above the active mining district, indicating that underground excavation was continuously driving overburden adjustment and surface structural degradation. These characteristics make the Zhengning mining area an ideal natural laboratory for investigating the progressive evolution from underground damage accumulation to catastrophic surface collapse in thick loess-covered mining environments.

2.2 Data sources

To capture the multi-scale evolution of mining-induced instability, four complementary datasets describing surface deformation, terrain morphology, topographic characteristics, and subsurface failure activity were integrated in this study.

(1) Sentinel-1 SAR observations. A total of 47 ascending Sentinel-1A images (Track 84) acquired between January 2024 and March 2026 were collected to derive time-series ground deformation. All images were acquired in Interferometric Wide Swath (IW) mode with VV polarization and an incidence angle of approximately 38.6° . The relatively dense temporal sampling enables continuous monitoring of deformation evolution throughout both active mining and post-mining adjustment stages.

(2) Topographic data. The 30-m Copernicus Digital Elevation Model (DEM) provided by the European Space Agency (ESA) was employed to remove topographic phase contributions during differential interferometric processing and to improve the geometric accuracy of time-series deformation retrieval.

(3) UAV photogrammetric survey. To characterize detailed geomorphological responses during the period of most intense surface deformation, a low-altitude UAV survey was conducted over the core subsidence zone. A total of 3,629 high-overlap visible-light photographs were acquired and processed using structure-from-motion photogrammetry to generate high-resolution Digital Orthophoto Maps (DOMs) and Digital Surface Models (DSMs). These products were subsequently used to identify

collapse pits, ground fissures, graben structures, scarp morphology, and the spatial extent of surface failure with centimetre-level detail, providing geomorphological evidence that complements the satellite-derived deformation observations.

(4) Microseismic catalogue. A continuous microseismic catalogue containing 6,684 recorded events between 1 September and 7 December 2025 was used to characterize underground rock-mass failure during longwall mining. The catalogue includes the occurrence time and spatial location of individual events, enabling quantitative analysis of temporal seismic activity, spatial migration of damage, and its coupling relationship with surface deformation evolution.

The combination of these four datasets provides complementary observations of the mining-induced failure process across multiple spatial and temporal scales. Time-series InSAR captures the long-term evolution of regional surface deformation, UAV surveys resolve localized geomorphological damage associated with structural collapse, and microseismic monitoring records the dynamic evolution of underground fracturing. Their integration establishes the observational basis for investigating the coupled evolution of subsurface damage accumulation and surface instability in deep, loess-covered coal mining areas.

3. Methods

3.1 Multi-source observation framework

Mining-induced ground instability involves coupled processes that evolve across different spatial and temporal scales. Surface deformation provides the large-scale manifestation of mining disturbance, localized geomorphological features record the final expression of deformation concentration, and microseismicity provides complementary information on subsurface damage evolution. Therefore, the three observation sources were integrated within a unified framework rather than analyzed as independent datasets.

The methodological framework consists of four interconnected components (Fig. 1). First, time-series Sentinel-1 SAR observations were processed using the Small Baseline Subset Interferometric Synthetic Aperture Radar (SBAS-InSAR) technique to reconstruct the spatial and temporal evolution of mining-induced surface deformation. Second, derivative-based kinematic analysis was applied to the InSAR displacement histories to obtain deformation velocity, acceleration, and spatial deformation gradients. These parameters were used to characterize changes in deformation dynamics and identify zones of deformation localization. Third, high-resolution UAV photogrammetry was used to characterize surface fissures, collapse pits, graben structures, scarps, and other localized geomorphological features and to examine their spatial relationship with the InSAR-derived deformation fields. Fourth, continuous microseismic observations were

used to characterize subsurface damage evolution. Cumulative Benioff strain was calculated as an indicator of progressive seismic damage accumulation and was subsequently compared with InSAR-derived surface deformation acceleration using cross-correlation analysis.

3.2 Time-series SBAS-InSAR deformation retrieval

Surface deformation was retrieved using the Small Baseline Subset InSAR (SBAS-InSAR) technique, which reconstructs deformation histories from multiple interferograms characterized by short temporal and spatial baselines while minimizing decorrelation effects (Berardino et al., 2002).

Sentinel-1 SAR images were first corrected using precise orbit ephemerides and co-registered to a common master image. Differential interferograms were subsequently generated with maximum temporal and perpendicular baseline thresholds of 90 days and 90 m, respectively, resulting in a connected interferometric network containing 126 interferometric pairs. Goldstein adaptive filtering was applied to suppress phase noise prior to phase unwrapping using the Minimum Cost Flow (MCF) algorithm (Goldstein, et al., 1998; Pepe & Lanari, 2006). Radar interferogram filtering for geophysical applications. *Geophysical Research Letters*, 25(21), 4035-4038.). Time-series deformation was then estimated by singular value decomposition (SVD), and residual atmospheric delays were mitigated using a spatiotemporal Gaussian - Markov filtering strategy in which low-frequency temporal components and high-frequency spatial components were separated and removed (Berardino et al., 2002).

Interferometric processing employed an 8:2 multilooking strategy to balance spatial resolution and phase stability. Pixels with temporal coherence lower than 0.35 were discarded from the inversion. Because InSAR measurements provide relative rather than absolute displacement, the final deformation time series was referenced to stable areas located outside the mining influence zone. The temporal displacement of each pixel was corrected by subtracting the displacement history of the selected reference pixel(s) (Wang, et al., 2026), thereby removing residual orbital ramps and common-mode phase errors and ensuring physically meaningful estimates of deformation velocity and acceleration.

3.3 Derivative-based kinematic analysis

Mining-induced collapse is characterized by rapid transitions in deformation dynamics rather than by cumulative displacement alone. Consequently, deformation velocity, acceleration, and spatial deformation gradients were employed as the principal kinematic indicators of instability evolution.

Direct differentiation of discrete InSAR observations is highly sensitive to atmospheric noise and temporal sampling intervals. To obtain robust derivative estimates, a one-dimensional Savitzky – Golay (SG) adaptive polynomial filter was independently applied to the displacement history of each coherent pixel (Savitzky & Golay, 1964). Because SG filtering simultaneously performs local polynomial fitting and analytical differentiation, it provides substantially greater noise resistance than conventional finite-difference approaches while preserving transient acceleration signals associated with progressive instability (Carlà et al., 2019).

Processing was performed in two stages. First, a five-epoch SG filter with a second-order polynomial was applied to suppress isolated observations while preserving the overall deformation trend. The smoothed displacement series were then interpolated onto a uniform daily time grid, after which first- and second-order derivatives were computed using a 31-day SG filter to obtain deformation velocity and acceleration, respectively. The selected window length represents a compromise between suppressing high-frequency atmospheric noise and retaining acceleration associated with mining-induced structural adjustment.

To characterize deformation localization, horizontal gradients of displacement and velocity were calculated on the regular deformation grid using finite-difference operators. The gradient magnitude identifies zones of concentrated strain surrounding subsidence basins and provides a quantitative indicator of deformation localization preceding surface rupture.

3.4 UAV-based geomorphological mapping

High-resolution UAV photogrammetry was employed to document the geomorphological expression of mining-induced structural failure and to validate deformation localization identified from InSAR observations.

A DJI Matrice 4E UAV acquired 3,629 overlapping aerial photographs covering the principal subsidence basin during the period of most intense deformation. Five ground control points (GCPs) measured using GNSS-RTK surveying were distributed uniformly throughout the survey area to improve georeferencing accuracy. Bundle adjustment yielded a three-dimensional root-mean-square error of approximately 0.4 mm, enabling the generation of Digital Orthophoto Maps (DOMs) and Digital Surface Models (DSMs) with a ground sampling distance of approximately 2.2 cm.

Ground fissures, collapse pits, graben structures, scarps, and other geomorphological features were interpreted through combined visual interpretation of orthophotos, surface texture, local relief, and slope discontinuities. These geomorphic features were subsequently compared with deformation velocity, acceleration, and gradient fields to

evaluate the spatial correspondence between surface failure and InSAR-derived instability indicators.

3.5 Coupled analysis of microseismic activity and surface instability

To investigate the temporal relationship between underground rock-mass failure and surface deformation acceleration, continuous microseismic observations were coupled with InSAR-derived kinematic parameters.

The cumulative Benioff strain was adopted as a proxy for progressive underground damage accumulation and was calculated from the recorded seismic energy of individual microseismic events (Benioff, 1951):

$$\varepsilon_B(t) = \sum_{i=1}^{M(t)} \sqrt{E_i}$$

where E_i is the seismic energy of the i -th event and $M(t)$ denotes the cumulative number of events up to time (t).

Daily maximum surface acceleration derived from the SG-filtered InSAR time series was used to characterize surface instability. Temporal coupling between cumulative Benioff strain and surface acceleration was quantified using discrete cross-correlation analysis:

$$R_{ae}(\Delta t) = \sum_k [\varepsilon_B(t_k) - \bar{\varepsilon}_B] [a_{max}(t_k + \Delta t) - \bar{a}]$$

where Δt represents the time lag between underground damage evolution and surface acceleration.

Because two high-energy seismic events ($\sim 10^9$ J) occurred during the monitoring period, direct correlation using daily energy release would be dominated by these extreme observations. To suppress the influence of episodic energy bursts while preserving the long-term evolution of underground damage, Benioff strain was accumulated within a 14-day moving window. This window length is comparable to the revisit interval of Sentinel-1 observations and therefore provides temporal consistency between seismic and deformation datasets. Time lags between -30 and $+30$ days were evaluated to identify statistically significant lead – lag relationships between subsurface fracturing and surface instability.

3.6 Exploratory multi-objective assessment of the damage indicator

The observed lead – lag relationship between cumulative Benioff strain and surface acceleration provides the physical basis for developing an operational early-warning strategy. Rather than selecting warning thresholds empirically, a multi-objective optimization framework based on the Non-dominated Sorting Genetic Algorithm II

(NSGA-II) was adopted to determine optimal warning parameters (Deb, et al., 2002; Zarchi, et al., 2025).

The predictor variable was defined as the normalized daily increment of cumulative Benioff strain after three-day moving-average smoothing. Hazardous deformation was defined as days when the absolute surface acceleration exceeded the 80th percentile of the observation period.

An early-warning rule was parameterized by two variables: the normalized Benioff-strain threshold θ and the trailing observation window w . An alarm was triggered whenever the smoothed Benioff-strain increment exceeded θ within the previous (w) days.

Model performance was evaluated using two conflicting objectives: maximizing the Probability of Detection (POD) and minimizing the False Alarm Rate (FAR). A warning was regarded as successful if at least one alarm occurred within the physically derived lead time preceding an acceleration event, whereas alarms not followed by hazardous acceleration during the corresponding forecast interval were classified as false alarms.

The NSGA-II optimization generated a Pareto-optimal solution set representing the trade-off between detection capability and false-alarm frequency. The knee point of the Pareto front, corresponding to the shortest Euclidean distance from the ideal solution (POD = 1, FAR = 0), was selected as the recommended operating threshold for practical deployment.

4. Results

4.1 Spatiotemporal evolution of mining-induced surface deformation

Time-series SBAS-InSAR observations reconstructed from 47 Sentinel-1 acquisitions between January 2024 and March 2026 reveal a continuous and progressive evolution of mining-induced surface deformation throughout the study area (Fig. 2 and Fig. S2). The final cumulative LOS displacement reached approximately -0.45 m, while the maximum mean deformation rate approached -3 mm day⁻¹, indicating sustained ground subsidence associated with longwall mining.

To illustrate the temporal evolution of deformation, three representative monitoring points (P1 – P3) were selected within the subsidence basin together with a stable reference point (P0) located outside the mining influence zone (Fig. 2). P1 and P2 coincide with the locations of the two major high-energy microseismic events recorded on 25 October and 6 December 2025, whereas P3 represents the maximum deformation zone above the previously mined 1802 – 1803 panels.

The original InSAR displacement series exhibit synchronous low-amplitude oscillations at all monitoring points (Fig. 2g), reflecting regional background signals that are unrelated to mining activities. Considering the extensive loess cover and pronounced seasonal environmental variations in the study area, these common oscillations are interpreted as residual atmospheric artefacts together with seasonal expansion and contraction of near-surface soils. After differential correction using the stable reference point P0, these common-mode signals were effectively removed, producing physically meaningful relative deformation histories (Fig. 2h).

The corrected deformation series reveal three distinct evolutionary stages.

(1) During Stage I (January – August 2024), deformation was concentrated above the 1802 – 1803 panels, forming a single elongated subsidence basin oriented approximately NNW – SSE. Subsidence at P3 developed steadily, whereas deformation at P1 and P2 remained negligible, indicating that mining influence was initially confined to the western panel group.

(2) During Stage II (September 2024 – May 2025), deformation progressively developed above the newly advancing 2803 – 2804 panels. Independent subsidence centres emerged, producing two clearly separated elongated basins corresponding to the two active mining districts. At this stage, deformation remained spatially isolated because the thick competent overburden retained sufficient arching capacity to limit mechanical interaction between adjacent panels.

(3) During Stage III (June 2025 – March 2026), deformation above the previously mined panels gradually stabilized, whereas rapid subsidence developed over the active 2803 – 2804 panels. The two initially independent deformation basins progressively expanded toward each other and eventually merged into a single composite subsidence basin. Simultaneously, deformation trajectories at P1, P2, and P3 became increasingly similar, suggesting that the overburden response evolved from isolated panel-scale deformation to large-scale structural interaction. Following completion of panel extraction, the geometry of the subsidence basin became progressively stabilized, with little subsequent change in its overall morphology.

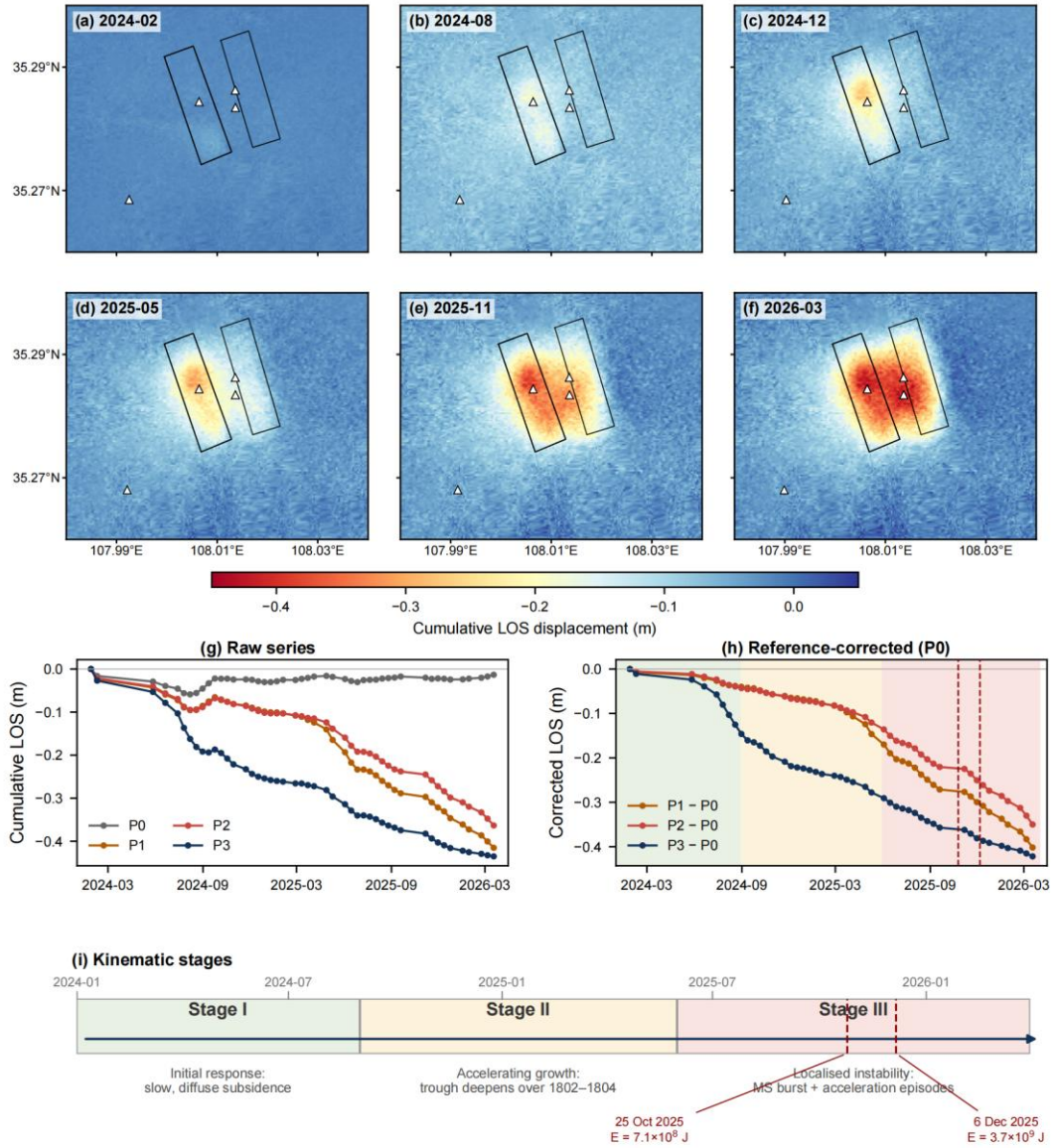


Fig. 2. Progressive surface deformation revealed by InSAR during longwall mining.

(a – f) Spatial evolution of cumulative LOS displacement from February 2024 to March 2026, illustrating the gradual development of the subsidence basin above the active mining panels. (g) Original cumulative LOS displacement time series at monitoring points P0 – P3. (h) Reference-corrected displacement series obtained by subtracting the stable reference point P0, highlighting mining-induced deformation. Background colours indicate the three deformation stages identified from the temporal evolution: Stage I (initial response), Stage II (accelerating subsidence), and Stage III (localized instability). Vertical dashed lines denote the occurrence of two high-energy microseismic events ($>10^8$ J). (i) Schematic timeline summarizing the three-stage evolution of progressive instability.

4.2 Spatial localization of deformation and surface instability

Although cumulative displacement provides a direct measure of the magnitude of mining-induced deformation, the spatial distribution of deformation gradients and the temporal evolution of deformation acceleration reveal additional information on where and when deformation becomes localized. The kinematic fields derived from the InSAR time series show a progressive concentration of deformation around the actively deforming zone (Fig. 3).

The instantaneous velocity field derived using the S-G method demonstrates continuous migration of the principal subsidence centre throughout mining (Fig. 3, Fig. S3 and Fig. S4). During 2024, the highest deformation rates were concentrated above the 1802 – 1803 panels before gradually weakening as mining progressed. By late 2024, a second deformation centre developed above the advancing 2803 – 2804 panels and subsequently migrated northeastward following the mining front. A notable feature emerged between April and November 2025, when the highest deformation velocities no longer occurred directly above either individual panel but instead became concentrated within the interaction zone between the two adjacent mining districts. This migration indicates that deformation localization was controlled not solely by active extraction but increasingly by mechanical interaction between neighbouring goafs. Profiles extracted along transect A – A' demonstrate the progressive strengthening and spatial localization of velocity, acceleration, and displacement-gradient anomalies (Fig. 3j – l).

The spatial relationship between these kinematic indicators and actual surface damage becomes particularly evident in the UAV observations. High-resolution UAV photogrammetry reveals a distinct zone of surface fissuring within the principal deformation area (Fig. 4a – c). The mapped fracture network includes several prominent tension cracks and localized surface deformation features. Fracture orientations show a dominant strike of approximately 10° – 20° , indicating a preferred structural orientation within the principal failure zone. Overlaying the UAV-derived fracture traces on the March 2026 InSAR displacement-gradient field demonstrates a close spatial correspondence between surface fissures and zones of elevated deformation gradients (Fig. 4e). Quantitative comparison further shows that deformation-gradient values at mapped crack vertices are significantly higher than those at randomly sampled locations within the InSAR domain (Fig. 4f).

Importantly, the surface ruptures do not preferentially coincide with the centres of maximum cumulative subsidence. Instead, they occur predominantly along deformation-localization belts characterized by strong spatial gradients. Thus, within the observed deformation field, the occurrence of localized surface failure is more closely associated with spatial concentration of deformation than with the absolute magnitude of cumulative displacement.

This result demonstrates the complementary value of InSAR and UAV observations: InSAR identifies the regional kinematic structure of deformation, whereas UAV observations resolve the centimetre-scale geomorphological expression of the localized deformation zones.

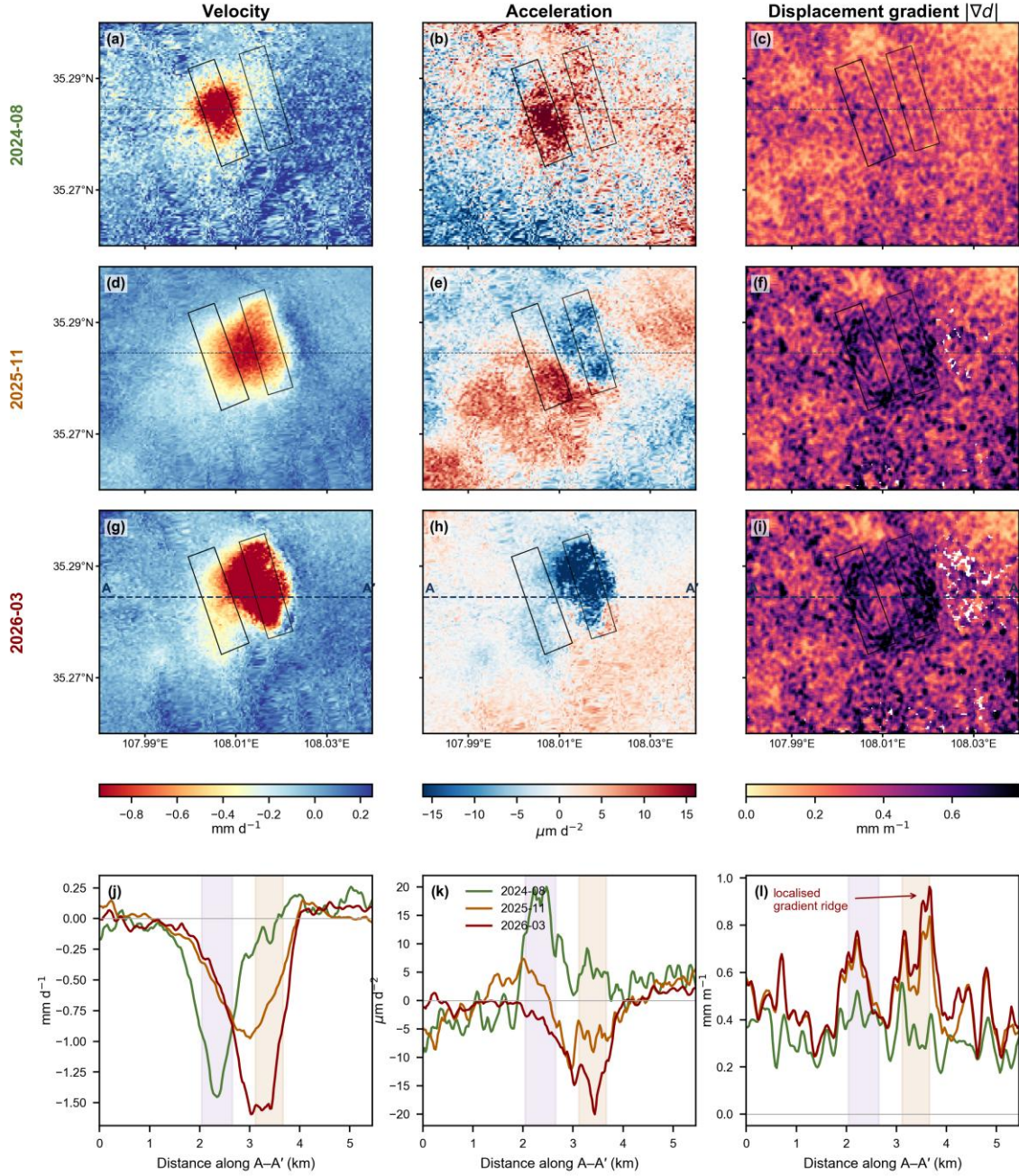


Fig. 3. Spatiotemporal evolution of deformation velocity, acceleration and displacement gradient.

(a – i) Maps of surface velocity, acceleration and displacement-gradient magnitude ($|\nabla d|$) for August 2024, November 2025 and March 2026. The displacement gradient progressively localizes into a narrow high-gradient ridge coinciding with the most active deformation zone. The dashed line A – A' indicates the location of profile extraction. (j – l) Profiles of velocity, acceleration and displacement gradient along A – A'. Shaded bands highlight the migration of the deformation centre and the emergence of localized strain concentration during the late deformation stage.

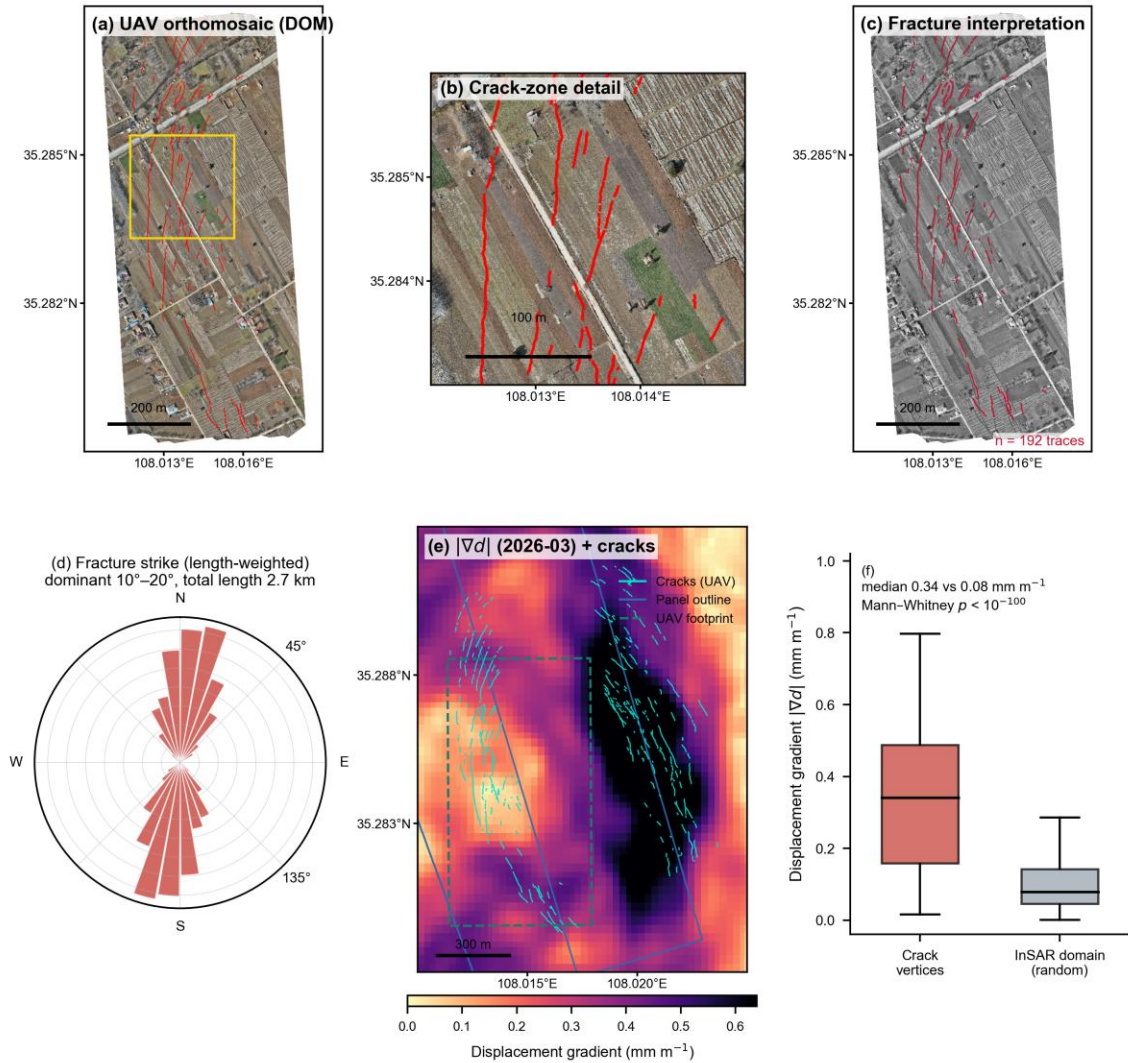


Fig. 4. UAV observations of surface fracturing and their correspondence with InSAR-derived deformation localization.

(a) UAV orthomosaic showing the distribution of surface tension cracks. (b) Enlarged view of the principal fracture zone. (c) Interpretation of mapped fractures extracted from UAV imagery. (d) Length-weighted rose diagram of fracture orientations, showing a dominant strike of approximately $10^\circ - 20^\circ$. (e) Overlay of mapped fractures on the InSAR displacement-gradient

field (March 2026), demonstrating close spatial agreement between fracture traces and localized deformation gradients. (f) Comparison of displacement-gradient values at mapped crack vertices and randomly sampled locations within the InSAR domain. The statistically significant difference confirms that deformation localization effectively predicts surface crack development.

4.3 Evolution of subsurface microseismic activity

The spatial distribution of the microseismic events is distinctly clustered rather than randomly distributed. Most events occur around the actively advancing 2803 – 2804 panels, particularly near the central leading edge of the mining front (Fig. 5a). In contrast, only limited seismic activity occurs above the previously mined 1802 – 1803 panels. This spatial pattern indicates that active excavation remains the dominant source of subsurface fracturing during the monitoring period, while localized secondary adjustment continues within the previously mined area. The temporal evolution of microseismic activity also shows a progressive increase in damage activity. Event frequency increases from early September through late October and remains elevated during November, reaching a maximum of 142 events day⁻¹ on 5 November 2025 (Fig. 5b). Periods of increased seismic activity broadly coincide with the emergence of pronounced acceleration anomalies in the InSAR-derived deformation series.

The cumulative Benioff-strain curve provides an integrated representation of the temporal evolution of seismic energy release (Fig. 5c). Two pronounced episodes of energy release are associated with the two major high-energy events during the monitoring period. These episodic energy-release features are superimposed on a more gradual increase in cumulative Benioff strain, indicating that subsurface damage consists of both distributed progressive fracturing and episodic high-energy failure. The Gutenberg – Richter distribution further indicates that the microseismic catalogue is dominated by small-scale events, while the relatively few high-energy events contribute disproportionately to the short-term energy-release response. This contrast provides an important basis for distinguishing the long-term accumulation of subsurface damage from short-duration structural failure events.

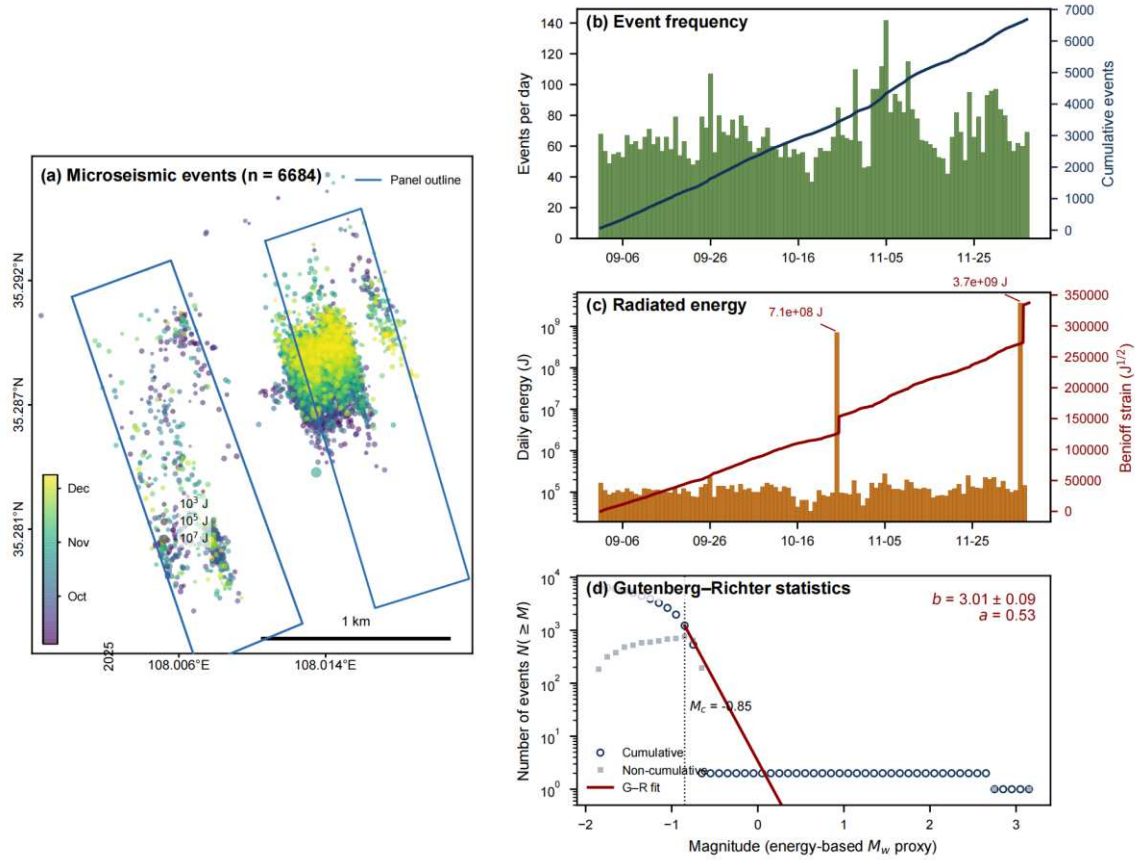


Fig. 5. Characteristics of underground microseismic activity during the monitoring period.

(a) Spatial distribution of 6684 recorded microseismic events coloured by occurrence time and scaled by radiated energy. (b) Daily and cumulative event frequencies. (c) Daily radiated energy together with cumulative Benioff strain, showing two pronounced energy-release episodes associated with high-energy events. (d) Gutenberg – Richter frequency – magnitude relationship derived from the energy-equivalent magnitude, indicating a completeness magnitude of $M_c \approx -0.85$ and a b-value of approximately 3.0, suggesting dominance of small-scale damage accumulation.

4.4 Temporal coupling between subsurface damage and surface deformation

The temporal relationship between subsurface damage accumulation and surface deformation was quantified by comparing cumulative Benioff strain with InSAR-derived surface deformation acceleration (Fig. 6).

The two time series exhibit a systematic temporal correspondence during the progressive deformation stage. Cross-correlation analysis between the first-differenced Benioff-strain series and surface acceleration yields a maximum correlation coefficient of $R = 0.47$ at a lag of approximately 17 days (Fig. 6b). The positive lag indicates that increases in the microseismic damage indicator precede subsequent increases in surface deformation acceleration. The approximately 17-day lead represents an observed temporal offset between the two monitoring signals, rather than a direct estimate of stress-propagation time or a universal warning period. The result indicates that the accumulation of distributed subsurface damage can precede the development of accelerated surface deformation by approximately two to three weeks under the observed mining and geological conditions.

The regression relationship after lag correction further demonstrates a positive correspondence between the two indicators (Fig. 6c). However, the moderate correlation coefficient also indicates substantial variability that cannot be explained by cumulative Benioff strain alone. This variability is consistent with the heterogeneous nature of the mining-induced deformation process and with the influence of other factors, including mining geometry, spatial deformation localization, and episodic structural failure. In addition to this delayed relationship, the two largest high-energy microseismic events exhibit a distinctly different response. The events occurring on 25 October and 6 December 2025 are associated with abrupt increases in surface deformation acceleration immediately following the underground energy-release episodes (Fig. 6d – e). These responses are nearly synchronous on the available observation timescale, contrasting with the approximately 17-day lead identified for progressive damage accumulation. Therefore, the observations indicate two distinct temporal response characteristics: (1) A progressive response, in which distributed microseismic damage accumulates before accelerated surface deformation by approximately 17 days; and (2) An episodic response, in which major high-energy underground failure events are accompanied by nearly synchronous surface deformation acceleration.

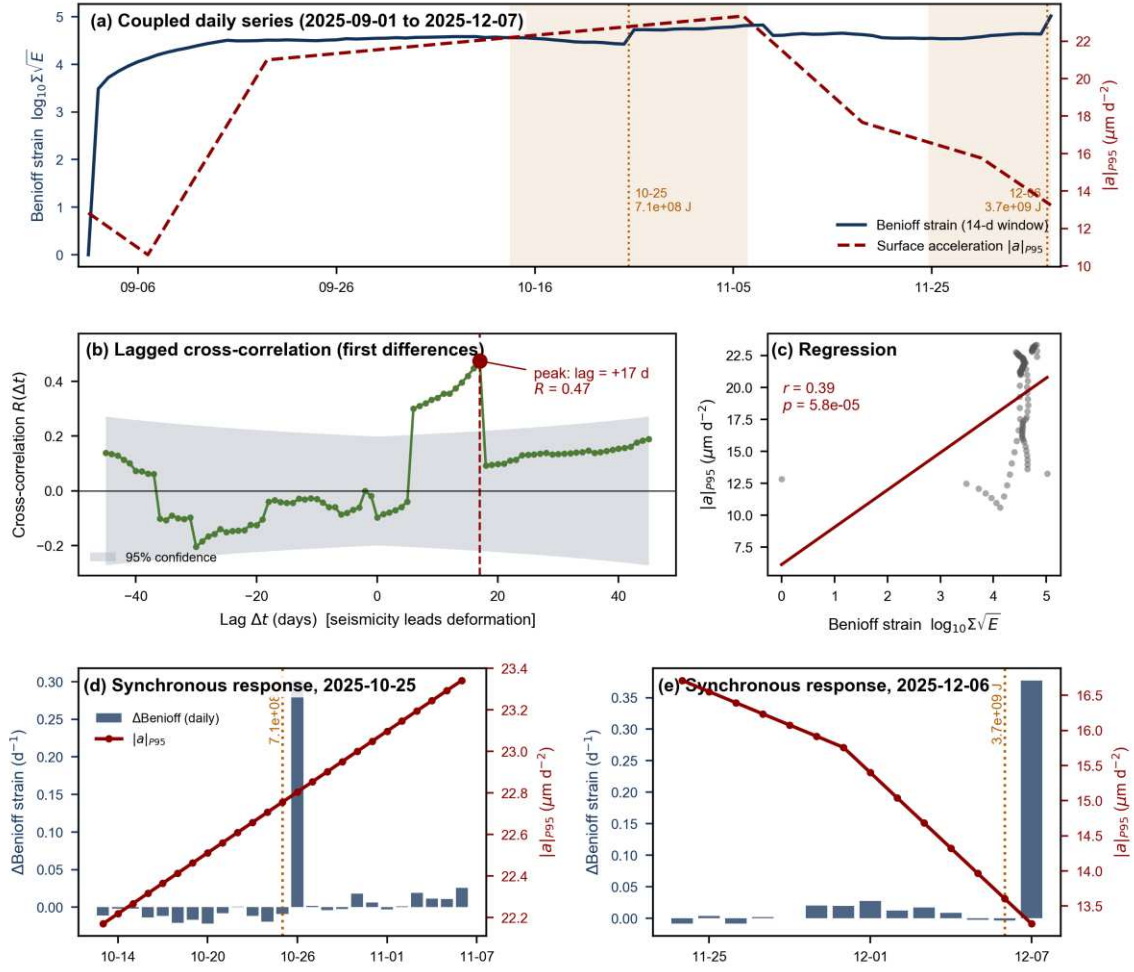


Fig. 6. Coupling between cumulative microseismic damage and surface deformation acceleration.

(a) Time series of cumulative Benioff strain and the 95th-percentile surface acceleration ($|a|_{P95}$). Shaded intervals indicate the progressive acceleration stage. (b) Cross-correlation between first-differenced Benioff strain and surface acceleration. Positive lag values indicate that Benioff strain leads deformation. The maximum correlation occurs at approximately 17 days. (c) Linear regression between Benioff strain and surface acceleration after lag correction. (d – e) Detailed responses associated with the two largest radiated-energy events, demonstrating nearly synchronous acceleration bursts in surface deformation immediately following major underground failures.

4.5 Exploratory assessment of the subsurface damage indicator

The identified 17-day precursor relationship provides a physically meaningful basis for operational hazard forecasting. Multi-objective optimization using NSGA-II generated a Pareto front comprising forty non-dominated solutions describing the trade-off between the probability of detection (POD) and the false alarm rate (FAR) (Fig. 7 and Fig. S11).

The optimal compromise corresponds to a normalized Benioff-strain threshold of approximately 0.04 with a trailing observation window of 19 days, achieving a POD of 1.0 while maintaining a FAR of approximately 0.63.

Although all hazardous acceleration episodes were successfully identified, the relatively high false alarm rate demonstrates that cumulative Benioff strain alone is insufficient for reliable operational forecasting. Many periods of elevated underground fracturing were not followed by immediate surface instability, implying that progressive damage accumulation represents a necessary but not sufficient condition for catastrophic collapse.

These results indicate that the observed lead time constitutes a physically robust precursor of instability transition, but practical early-warning systems will require the integration of additional indicators—including deformation acceleration, spatial strain localization, and mining geometry—to improve forecasting reliability while reducing false alarms.

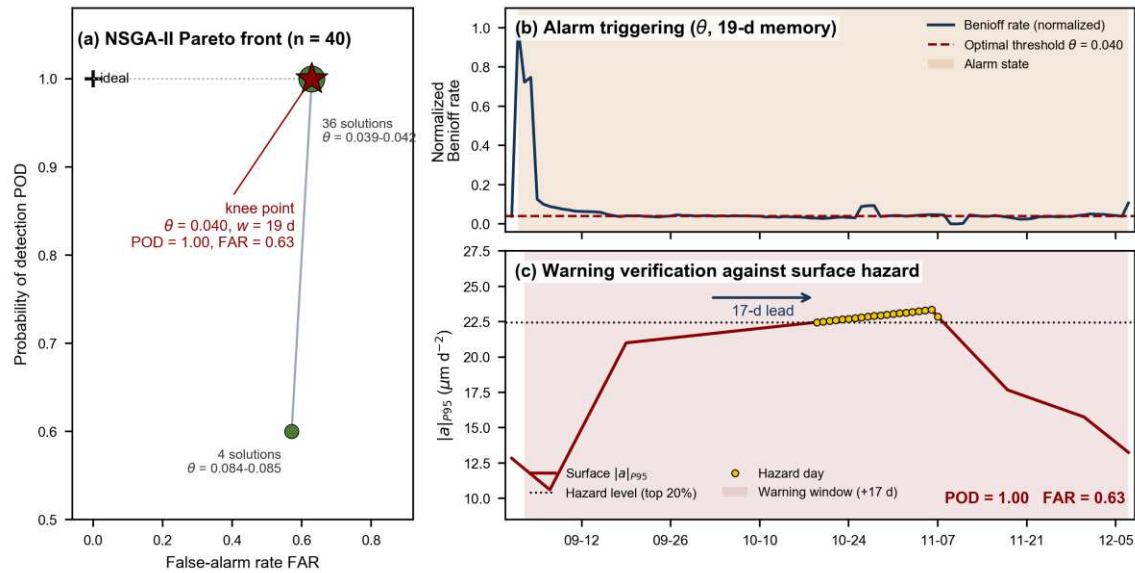


Fig. 7. Multi-source characterization of progressive instability

(a) Pareto-optimal solutions obtained using the NSGA-II multi-objective optimization algorithm. The selected knee-point solution corresponds to an alarm threshold $\theta = 0.040$ and a memory window of 19 days. (b) Alarm states generated from the optimized Benioff-rate model. (c) Comparison between warning periods and observed high-acceleration surface hazard intervals. The optimized model successfully predicts the deformation hazard window approximately 17 days in advance, yielding a probability of detection (POD) of 1.00 and a false-alarm rate (FAR) of 0.63.

5. Discussion

5.1 Progressive evolution of subsidence reflects changing overburden connectivity

A major finding of this study is that mining-induced surface deformation did not develop as an instantaneous response to individual longwall panels. Instead, the InSAR observations reveal a progressive transition from spatially separated deformation centres to an integrated subsidence basin. This evolution occurred over approximately six months, during which the initially independent deformation zones associated with adjacent panels progressively expanded and interacted.

In the Zhengning mining district, surface deformation represents the superposition of multiple longwall panels extracted successively within the same mining system. During the early mining stage, each panel generated an independent subsidence basin controlled primarily by local overburden bending and the conventional angle of draw, consistent with classical mining subsidence theory (Peng, 1992; Singh and Yadav, 1995). The clear spatial separation between adjacent basins indicates that the thick competent sandstone roof remained mechanically continuous, effectively preventing stress transfer between neighbouring goafs. As mining progressed, repeated roof caving and sequential breakage of subordinate key strata progressively weakened the structural integrity of the overburden. Mechanical loads were repeatedly redistributed among adjacent rock bridges until the remaining key strata could no longer maintain structural partitioning (Peng, et al., 2011). Consequently, the two initially independent subsidence basins gradually interacted and ultimately merged into a single composite deformation basin.

This transition is important because it demonstrates that the geometry of a mining-induced subsidence basin is not determined solely by the instantaneous location of active excavation. Instead, the observed surface pattern records the cumulative evolution of deformation and the changing connectivity of the overburden response. Though InSAR cannot directly resolve the evolution of individual key strata or internal stress redistribution, the progressive expansion and coalescence of surface deformation provide indirect evidence that the deformation system changes from relatively independent panel-scale responses to a more interconnected state (Sun, et al., 2024).

5.2 Deformation localization provides a more informative surface indicator than cumulative subsidence

The combined InSAR and UAV observations provide an important insight into the relationship between surface deformation magnitude and surface failure. The mapped fissures and localized geomorphological features are preferentially distributed along

zones of high deformation gradients rather than at the centres of maximum cumulative subsidence. This indicates that the spatial organization of deformation may be more informative for identifying localized surface instability than displacement magnitude alone.

Cumulative displacement represents the integrated deformation that has occurred over the observation period, whereas spatial deformation gradients quantify how rapidly deformation changes across the surface. The latter therefore provides information on deformation concentration (Xu & Zeng, 2009; Shen, et al., 2025). Cui et al. (2001) emphasized that the damage potential during subsidence development is closely related to progressive and differential deformation, whereas the central part of a mature subsidence basin may experience relatively small surface slope and curvature despite large cumulative displacement. This distinction provides an important interpretation of the present results. The maximum cumulative subsidence identifies the locations where the largest total displacement has occurred, but the deformation-gradient field identifies zones where neighbouring surface elements experience substantially different deformation. Such spatial heterogeneity provides a more direct kinematic representation of deformation localization and therefore has potential relevance for identifying zones susceptible to surface cracking and localized failure.

The UAV observations provide independent high-resolution evidence for this interpretation. The centimetre-scale DOM and DSM reveal surface fissures, collapse pits, graben structures, and scarps that cannot be adequately characterized using the regional InSAR displacement field alone (Zhao, et al., 2021). The close spatial correspondence between UAV-mapped ground fissures and zones of elevated deformation gradients demonstrates that tensile failure preferentially develops where deformation localizes rather than where total settlement reaches its maximum. This observation agrees with strain-localization theory, in which fracture initiation is governed primarily by concentrated tensile deformation instead of absolute displacement magnitude (Wang, et al., 2003).

This complementarity of the two observation systems is particularly relevant for Earth observation-based geohazard monitoring. Satellite InSAR provides broad spatial coverage and long-term temporal information, but its spatial resolution and line-of-sight measurement geometry limit its ability to characterize individual surface cracks. UAV observations provide the opposite advantage: they resolve localized geomorphological features at centimetre-scale resolution but cover a substantially smaller area and are generally acquired intermittently. Their integration therefore allows the deformation field identified at regional scale to be linked with its high-resolution surface expression.

5.3 Linking subsurface damage accumulation with surface deformation

The microseismic observations provide a complementary perspective on the processes occurring beneath the ground surface. Previous studies have established that mining-induced microseismicity can reflect stress redistribution, fracture development, and overburden movement during longwall extraction. Cheng et al. (2017), for example, demonstrated that the spatial and energetic distribution of microseismic events can be used to identify different zones of mining-induced strata movement and fracture development. Similarly, Ghosh and Sivakumar (2018) showed that temporal variations in microseismic activity can provide information on fracture propagation, stress redistribution, and roof-fall-related instability in longwall mining.

In the present study, the microseismic catalogue is dominated by small events, with a completeness magnitude of approximately $M_c \approx -0.85$ and a high b-value of approximately 3.0. The spatial concentration of events around the actively advancing panels indicates that the observed seismicity primarily records progressive subsurface fracturing associated with active excavation. This interpretation is consistent with previous microseismic studies in longwall mines, where distributed low-energy events are commonly associated with progressive roof and overburden fracturing and stress redistribution.

The temporal relationship between cumulative Benioff strain and surface deformation acceleration provides an additional connection between subsurface and surface observations. In our study, cross-correlation analysis identifies a maximum correlation of $R=0.47$ at a lag of approximately 17 days, indicating that the cumulative microseismic damage indicator precedes the observed acceleration of surface deformation.

This temporal separation is consistent with the general concept that subsurface fracture and overburden adjustment may precede the development of pronounced surface deformation. Field observations and modelling studies have shown that surface subsidence may lag behind active mining and that the timing of surface response depends on the mechanical properties and structure of the overburden (Zhang et al., 2021). In addition, recent integrated monitoring studies have demonstrated that progressive subsurface fracture activity can accompany continuous or accelerated surface deformation before major collapse or instability (Wang, et al., 2026).

However, the moderate correlation coefficient obtained in our study is equally important. It indicates that surface deformation acceleration cannot be explained by cumulative microseismic damage alone. Mining geometry, overburden structure, deformation localization, and episodic high-energy failure may all influence the surface response. This interpretation is consistent with recent studies showing that the relationship between seismicity and surface deformation depends strongly on the geological structure and mining configuration. For example, strong mining-induced seismic events associated

with thick-hard strata can produce pronounced surface responses when large-scale overburden fractures occur, whereas lower-energy seismicity may have limited direct surface expression (Zhang, et al., 2025).

5.4. Dual-timescale responses reveal different modes of instability evolution

An important feature emerging from the integrated observations is the existence of two distinct temporal response patterns. The first is a progressive, delayed response, in which cumulative microseismic damage precedes surface deformation acceleration by approximately 17 days. The second is a rapid, near-synchronous response, in which the two largest high-energy microseismic events are followed by abrupt changes in surface deformation acceleration. These observations suggest that mining-induced instability cannot necessarily be represented by a single characteristic timescale.

The progressive response is consistent with the concept of distributed damage accumulation. Numerous small microseismic events may occur during continued excavation as the surrounding rock mass undergoes stress redistribution and progressive fracturing. Previous microseismic studies have demonstrated that event frequency, spatial distribution, and energy release can evolve systematically with mining advance and overburden deformation (Cheng et al., 2017). In this context, the approximately 17-day lag identified in our study is best interpreted as an observational lead between subsurface damage accumulation and subsequent surface deformation acceleration, rather than as a direct estimate of stress-transfer or fracture-propagation time. The distinction is important because the temporal sampling of Sentinel-1 constrains the precision with which short-term surface acceleration can be resolved.

The second response pattern is fundamentally different. The two high-energy microseismic events are associated with abrupt changes in surface deformation acceleration over a much shorter timescale. Similar rapid surface responses have been documented following strong mining-induced seismic events. For example, a case study in the Upper Silesian Coal Basin identified a rapid ground response following a strong mining-induced seismic event, with the observed deformation closely corresponding to the seismological interpretation (Rudziński, et al., 2019). Other studies have also reported strong coupling between large-energy mining-induced seismic events, overburden fracture, and abrupt increases in surface subsidence (Zhang, et al., 2025).

The coexistence of these two temporal responses therefore suggests that the surface manifestation of mining-induced instability may occur through at least two observational pathways. The first pathway involves distributed subsurface damage accumulation followed by delayed surface acceleration, whereas the second involves episodic high-energy structural failure accompanied by a rapid surface response. Importantly, these two pathways should not be interpreted as completely independent mechanisms. Rather, they may represent different expressions of an evolving overburden system. Distributed

microseismic damage may progressively modify the mechanical state of the rock mass, while episodic high-energy events may occur when localized structural conditions permit rapid energy release. The subsequent surface response depends on the spatial extent and depth of the deformation source as well as the mechanical structure of the overburden.

The dual-timescale response identified here consequently provides a useful conceptual basis for multi-source monitoring. Microseismicity may become informative during the subsurface damage-accumulation stage, while InSAR-derived acceleration and deformation gradients become increasingly informative when the deformation begins to localize at the surface. UAV observations can then provide high-resolution confirmation of the resulting surface fissures and localized geomorphological damage. Therefore, the principal implication is not that the 17-day interval constitutes a universal precursor time, but that subsurface damage accumulation and surface deformation may evolve on different characteristic timescales. Recognizing this temporal separation is important when interpreting multi-source observations and when designing monitoring strategies for mining-induced ground instability.

5.5 A conceptual model of progressive instability in thick loess-covered mining areas

Based on the integrated observations presented in this study, a conceptual model describing progressive instability in deep loess-covered coalfields is proposed (Fig. 8).

From a vertical perspective, longwall extraction initiates periodic loading and brittle failure of thick competent key strata at depth. Microseismic events generated during this stage record the progressive accumulation of distributed damage within the overburden. As fracturing propagates upward through successive rock layers, deformation becomes increasingly localized until it reaches the thick Quaternary loess cover. Owing to its weak structure and high collapsibility, the loess layer attenuates and delays deformation transmitted from depth while simultaneously concentrating tensile strain near the margins of the developing subsidence basin (Cao et al., 2025). Consequently, surface failure is expressed primarily as localized fissures, grabens, and collapse pits distributed along high-gradient deformation belts rather than within the basin centre.

From a plan-view perspective, instability evolves through four successive stages. During the independent subsidence stage, each longwall panel produces an isolated deformation basin with limited interaction. During the interaction and damage accumulation stage, stress redistribution between adjacent panels promotes fracture connectivity, increasing both deformation acceleration and microseismic activity. During the structural failure stage, large-scale breakage of key strata generates high-energy microseismic events accompanied by abrupt transitions in surface kinematics. Finally, during the basin coalescence stage, mechanical partitioning disappears, adjacent deformation basins merge

into a single regional subsidence basin, and the system gradually enters a phase of post-mining adjustment.

This conceptual model emphasizes that catastrophic surface collapse is not a discrete event but the final manifestation of long-term underground structural evolution, providing a unified framework linking deep rock-mass damage, overburden deformation, and surface geomorphological failure.

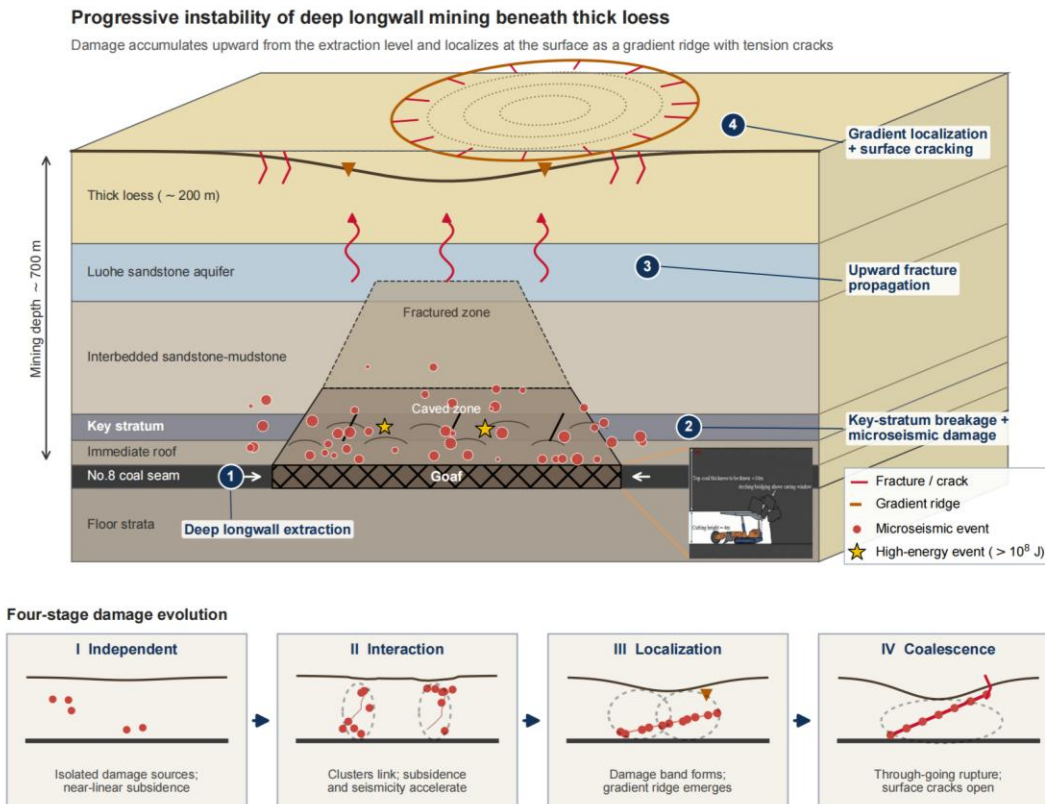


Fig. 8. Conceptual model illustrating progressive instability induced by deep longwall mining beneath thick loess.

Longwall extraction initiates localized damage within the immediate roof and key strata. Progressive fracture propagation transfers deformation upward through the overburden, eventually producing localized deformation gradients and surface tensile cracking. Four evolutionary stages are distinguished: (I) isolated damage initiation, (II) interaction and linkage of damage clusters, (III) localization of deformation into a high-gradient band, and (IV) coalescence into through-going surface fractures. High-energy microseismic events are interpreted as rapid stress-release episodes superimposed on continuous damage accumulation.

6. Conclusions

This study integrated time-series Sentinel-1 InSAR, UAV photogrammetry, and continuous microseismic monitoring to investigate the spatiotemporal evolution and multi-scale characteristics of mining-induced ground instability in a deep longwall mining area beneath thick loess. The main conclusions are as follows.

(1) Mining-induced surface deformation developed progressively from localized deformation to interacting and coalescing subsidence basins.

The 47 Sentinel-1 acquisitions revealed a cumulative LOS displacement of approximately -0.45 m, with maximum deformation rates approaching -3 mm day $^{-1}$. The deformation evolved through three stages, from localized deformation above previously mined panels, to the development of spatially separated deformation centres, and finally to their progressive interaction and coalescence. This evolution demonstrates that the observed surface deformation was controlled not only by the location of active mining but also by the progressive spatial integration of deformation responses.

(2) Surface fissuring was more closely associated with deformation localization than with maximum cumulative subsidence.

The combined InSAR and UAV observations showed that surface fissures preferentially occurred within zones characterized by strong spatial deformation gradients rather than at the centres of maximum cumulative displacement. High-resolution UAV observations independently identified localized fissures and other geomorphological features within these deformation-localization zones. This result highlights the importance of incorporating deformation kinematics and spatial gradients, rather than relying solely on cumulative displacement, when interpreting localized mining-induced surface damage.

(3) Subsurface microseismic damage exhibited a measurable temporal relationship with subsequent surface deformation acceleration.

A total of 6684 microseismic events were detected during the monitoring period, with a completeness magnitude of approximately $M_c = -0.85$ and a Gutenberg – Richter b -value of approximately 3.0. Cross-correlation between cumulative Benioff strain and InSAR-derived surface deformation acceleration yielded a maximum correlation coefficient of $R = 0.47$ at an approximately 17-day lag, with microseismic damage accumulation preceding surface deformation acceleration. This relationship indicates an observational temporal separation between subsurface damage accumulation and its surface expression, while the moderate correlation also demonstrates that microseismic damage alone cannot fully explain the surface deformation response.

(4) Mining-induced ground instability exhibited distinct slow and rapid temporal responses.

The approximately 17-day lag represents a progressive response associated with distributed subsurface damage accumulation, whereas the two major high-energy microseismic events were accompanied by nearly synchronous changes in surface deformation acceleration. These observations indicate that mining-induced instability does not evolve according to a single characteristic timescale. Instead, progressive damage accumulation and episodic high-energy failure represent complementary temporal expressions of the evolving deformation system.

(5) The integration of InSAR, UAV, and microseismic observations provides a more complete observational framework for mining-induced ground instability.

InSAR captures the regional evolution and kinematics of surface deformation, UAV photogrammetry resolves localized surface geomorphological damage, and microseismic monitoring provides complementary information on subsurface damage activity. Their integration establishes observational links between subsurface damage accumulation, surface deformation localization, and localized surface failure, providing a multi-scale observation framework for investigating mining-induced geohazards.

Overall, the results demonstrate that mining-induced ground instability should be interpreted as a progressive, spatially localized, and multi-timescale process, rather than simply as an increase in cumulative surface subsidence. The identified temporal and spatial relationships provide a basis for developing multi-source observation strategies for monitoring mining-induced ground deformation and surface instability. Further studies involving multiple mining sites, denser temporal observations, and additional geological and geomechanical constraints are required to evaluate the transferability of these relationships to different mining and geological settings.

Acknowledgements

We thank the mine monitoring team for access to the microseismic catalogue and mining-engineering vectors. This study used only open-source scientific-computing tools.

Declaration of Competing Interest

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

References

- Bell FG, Stacey TR, Genske DD (2000) Mining subsidence and its effect on the environment: some differing examples. *Environ Geol* 40:135 – 152.
- Berardino P, Fornaro G, Lanari R, Sansosti E (2002) A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Trans Geosci Remote Sens* 40:2375 – 2383.
- Cao J et al (2025) Study on the mechanism of mining-induced seismicity driven by failure of hard and extremely thick rock strata. *Front Earth Sci* 13:1556612.
- Carlà T, Intrieri E, Raspini F et al (2019) Perspectives on the prediction of catastrophic slope failures from satellite InSAR. *Sci Rep* 9:14137.
- Chen Y, Xu D, Qi Y, Huang P, Sun W, Xu W et al (2023) Integration of DInSAR-PS-stacking and SBAS-PS-InSAR methods to monitor mining-related surface subsidence. *Remote Sens* 15:2691.
- Cheng G, Ma T, Tang C, Liu H, Wang S (2017) A zoning model for coal mining-induced strata movement based on microseismic monitoring. *Int J Rock Mech Min Sci* 94:123 – 138. <https://doi.org/10.1016/j.ijrmms.2017.03.001>
- Cheng X et al (2023) Study on deep learning methods for coal-burst risk prediction based on mining-induced seismicity quantification. *Geomech Geophys Geo-Energy Geo-Resour* 9:122.
- Cheng Q (2026) Mechanism of top-coal cavability improvement by hydraulic fracturing preconditioning. *J Ind Saf*. <https://doi.org/10.1016/j.jinse.2026.04.003>
- Cui X, Wang J, Liu Y (2001) Prediction of progressive surface subsidence above longwall coal mining using a time function. *Int J Rock Mech Min Sci* 38:1057 – 1063. [https://doi.org/10.1016/S1365-1609\(01\)00061-2](https://doi.org/10.1016/S1365-1609(01)00061-2)
- Deb K, Pratap A, Agarwal S, Meyarivan T (2002) A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans Evol Comput* 6:182 – 197. <https://doi.org/10.1109/4235.996017>
- Du Q, Guo G, Li H, Sun J, Hu Z (2026) Overlying strata movement characteristics and water conducting fracture zone height prediction for deep coal mining in arid Western China. *Sci Rep* 16:14156. <https://doi.org/10.1038/s41598-026-46768-4>
- Ferretti A, Prati C, Rocca F (2001) Permanent scatterers in SAR interferometry. *IEEE Trans Geosci Remote Sens* 39:8 – 21.

Ghosh GK, Sivakumar C (2018) Application of underground microseismic monitoring for ground failure and secure longwall coal mining operation: a case study in an Indian mine. *J Appl Geophys* 150:21 – 39. <https://doi.org/10.1016/j.jappgeo.2018.01.004>

Goldstein RM, Werner CL (1998) Radar interferogram filtering for geophysical applications. *Geophys Res Lett* 25:4035 – 4038.

Guangyao S, Wu C, Wang S, Xu L (2020) Prediction of relatively high-energy seismic events using spatial – temporal parametrisation of mining-induced seismicity. *Rock Mech Rock Eng* 53:5111 – 5132.

He MC, Xie HP, Peng SP et al (2005) Study on rock mechanics in deep mining engineering. *Chin J Rock Mech Eng* 24:2803 – 2813. (in Chinese)

Jiang YD, Pan YS, Jiang FX et al (2014) State of the art review on mechanism and prevention of coal bumps in China. *J China Coal Soc* 39:205 – 213. (in Chinese)

Li J, Li H, Li W, Li L, Jiang P, Du M (2023) Water inrush mechanism and prevention for thick coal mining under an extremely thick glutenite layer: a case study in the southwest of the Ordos Basin. *Bull Eng Geol Environ* 82:389.

Pawluszek-Filipiak K, Borkowski A (2020) Integration of DInSAR and SBAS techniques to determine mining-related deformations using Sentinel-1 data: the case study of Rydułtowy mine in Poland. *Remote Sens* 12:242.

Peng LJ, Zhao XD, Li SC (2011) Simulation study on surface subsidence law in deep mining. *Rock Soil Mech* 32:1910 – 1914. (in Chinese)

Peng SS (1992) Surface subsidence engineering. Society for Mining, Metallurgy, and Exploration, Littleton, CO, USA.

Peng SS (2015) Topical areas of research needs in ground control—a state of the art review on coal mine ground control. *Int J Min Sci Technol* 25:1 – 6.

Pepe A, Lanari R (2006) On the extension of the minimum cost flow algorithm for phase unwrapping of multitemporal differential SAR interferograms. *IEEE Trans Geosci Remote Sens* 44:2374 – 2383.

Petrillo G et al (2024) A Bayesian earthquake forecasting approach based on the epidemic type aftershock sequence model. *Earth Planets Space* 76:80.

Qian MG, Xu JL (2019) Coal mining and strata movement. *J China Coal Soc* 44:973 – 984. (in Chinese)

Qin ZH, Chen CQ, Li FH et al (2021) Seismic mechanism and prevention technology of solid coal roadway in deep buried structural area. *Coal Sci Technol* 49:87 – 92. (in Chinese). <https://doi.org/10.13199/j.cnki.cst.2021.11.011>

Rudziński Ł, Mirek K, Mirek J (2019) Rapid ground deformation corresponding to a mining-induced seismic event followed by a massive collapse. *Nat Hazards* 96:461 – 471. <https://doi.org/10.1007/s11069-018-3552-0>

Savitzky A, Golay MJE (1964) Smoothing and differentiation of data by simplified least squares procedures. *Anal Chem* 36:1627 – 1639. <https://doi.org/10.1021/ac60214a047>

Shen Z, Wang Y, Wang T, Zhao F, Du S, Li L, Xu X, Liu J, Huo W, Zou G (2025) Mining-induced subsidence boundary delineation using dual-feature clustering of InSAR-derived deformation gradient. *Remote Sens* 17:3494. <https://doi.org/10.3390/rs17203494>

Singh RP, Yadav RN (1995) Prediction of subsidence due to coal mining in Raniganj coalfield, West Bengal, India. *Eng Geol* 39:103 – 111.

Sun QX, Zhang Y, Chen QT et al (2024) Review of 70-year research on mining subsidence in China and technical prospects. *China Min* 33:86 – 99. (in Chinese)

Wang B, Zhu W, Zhao C, Li G, Yang L, Li W, Yan B, Cai X (2026) Multireference-point InSAR time series with hypothesis testing and constrained least squares. *IEEE Geosci Remote Sens Lett* 23:4010805. <https://doi.org/10.1109/LGRS.2026.3704177>

Wang H, Chen J, Liang W, Xu G (2026) Long-term post-mining deformation evolution and failure mechanism of the Rongxing gypsum mine revealed by SBAS-InSAR and microseismic monitoring. *Remote Sens* 18:1584. <https://doi.org/10.3390/rs18101584>

Wang K, Ma K, Tang C et al (2023) Study on deep mining-induced strata behavior based on the evolutionary laws of multiple indices from microseismic monitoring. *Rock Mech Rock Eng* 56:6481 – 6501. <https://doi.org/10.1007/s00603-023-03411-2>

Wang L, Deng K, Zheng M (2020) Research on ground deformation monitoring method in mining areas using the probability integral model fusion D-InSAR, sub-band InSAR and offset-tracking. *Int J Appl Earth Obs Geoinf* 85:101981.

Wang XB, Pan YS, Ren WJ (2003) Instability criterion of shear failure for rock specimen based on gradient-dependent plasticity. *Chin J Rock Mech Eng* 22:747 – 750. (in Chinese)

- Witkowski W, Łucka M, Sudhaus H, Barańska A, Hejmanowski R, Guzy A (2023) Research on the mechanism of induced seismicity utilizing InSAR-retrieved land subsidence, source model, and geological constraints. EGU General Assembly 2023, Vienna, Austria, 24 – 28 April 2023, EGU23-9584. <https://doi.org/10.5194/egusphere-egu23-9584>
- Xie HP, Gao F, Ju Y et al (2015) Quantitative definition and analysis of deep mining. J China Coal Soc 40:1 – 10. (in Chinese)
- Xu Q, Zeng YP (2009) Research on acceleration variation characteristics of creep landslide and early-warning prediction indicator of critical sliding. Chin J Rock Mech Eng 28:1099 – 1106. (in Chinese). <https://doi.org/10.3321/j.issn:1000-6915.2009.06.003>
- Xu ZJ, Lin ZG, Zhang MS (2007) Loess in China and loess landslides. Chin J Rock Mech Eng 26:1297 – 1312. (in Chinese)
- Yin X, Qiu J, Wang H, Zhou L, Wang S, Liu Y, Yang X (2026) A multi-source monitoring framework for mining-induced geohazards integrating time-series InSAR and microseismic observations. Int J Digit Earth 19:2706887. <https://doi.org/10.1080/17538947.2026.2706887>
- Zarchi M, Nazari RA, Tee KF (2025) Explainable nature-inspired optimization via virtual and actual multi-objective strategies to establish a smart earthquake early warning system. Appl Soft Comput 113698.
- Zhang G, Zhang G, Zhou G et al (2025) Joint response of surface subsidence and strong mine earthquake under high-positioned and thick-hard strata in deep coal mine. Sci Rep 15:1538. <https://doi.org/10.1038/s41598-025-85356-w>
- Zhang K, Bai L, Wang P, Zhu Z (2021) Field measurement and numerical modelling study on mining-induced subsidence in a typical underground mining area of northwestern China. Adv Civ Eng 2021:5599925. <https://doi.org/10.1155/2021/5599925>
- Zhang Q et al (2024) Strong mining-induced earthquakes produced by the fracturing of key strata during deep coal mining. Int J Geomech 24:04024080.
- Zhao D, Wu Q, Wang HY, Zhang XH, Ao N, Zhang Y et al (2022) Study on mining subsidence deformation and failure in loess gully region of Ordos. Coal Sci Technol 50(S02):185 – 195. (in Chinese)
- Zhao Y, Sun B, Liu S, Zhang C, He X, Xu D, Tang W (2021) Identification of mining induced ground fissures using UAV and infrared thermal imager: temperature variation

and fissure evolution. ISPRS J Photogramm Remote Sens 180:45 – 64.
<https://doi.org/10.1016/j.isprsjprs.2021.08.005>

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryMaterials.docx](#)