mining

MDPI

Article

Persistent Mining-Induced Subsidence Two Decades After Underground Coal Exploitation: Evidence from Multi-Temporal GNSS Monitoring

Teodora Gavrilescu [1,*] and Cornel Păunescu [2]

[1] Doctoral School of Geology, Faculty of Geology and Geophysics, University of Bucharest, 050095 Bucharest, Romania
[2] Faculty of Geology and Geophysics, University of Bucharest, 050095 Bucharest, Romania; cornelpaun@gmail.com
* Correspondence: teo_gvr@yahoo.com

Abstract

Mining-induced subsidence represents one of the most significant long-term geomechanical hazards associated with underground coal exploitation, often continuing for decades after mining activities have ceased. Understanding the persistence and spatial distribution of post-mining ground deformation is essential for evaluating residual geological hazards and improving long-term monitoring strategies in former mining regions. This study investigates the long-term evolution of mining-induced subsidence in the Maleia sector of the Jiu Valley Coal Basin (Romania), an area historically affected by intensive underground coal extraction. A geodetic monitoring network consisting of seventeen permanent benchmarks, initially established in 2006, was reoccupied and remeasured using Global Navigation Satellite System (GNSS) technology in 2026. The comparative analysis was performed against historical measurements acquired during the 2007 monitoring campaign, providing a nineteen-year temporal framework for deformation assessment. Analysis of vertical displacements revealed persistent subsidence at all monitored benchmarks, confirming the continued post-mining adjustment of the geological structure. Measured cumulative vertical displacements ranged from −0.082 m to −3.853 m, with the highest deformation recorded at benchmark R14. The calculated average annual subsidence rates reached values of up to −0.203 m/year and are reported as normalized indicators of cumulative deformation over the nineteen-year observation interval. The results demonstrate that mining-induced geomechanical instability may persist for decades after underground mining has ceased, emphasizing the necessity of long-term monitoring strategies in former coal mining regions affected by residual geological hazards. This study provides one of the few long-term GNSS field datasets documenting delayed mining-induced subsidence over a nineteen-year observation period in an underground coal basin, contributing rare field evidence of persistent post-mining geomechanical evolution in Eastern Europe.

Keywords: mining subsidence; GNSS monitoring; post-mining deformation; engineering geology; underground coal mining; ground deformation; geomechanical hazard

Check for updates

Academic Editors: Moshood Onifade, Samson Bada, Manoj Khandelwal and Xuan-Nam Bui

Received: 8 July 2026
Revised: 27 July 2026
Accepted: 28 July 2026
Published: 30 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Underground coal mining is widely recognized as one of the major anthropogenic factors capable of generating long-term geomechanical disturbances within the geological environment. Among the most significant consequences associated with underground

extraction activities is mining-induced subsidence, a complex deformation process that affects the stability of overlying rock formations and progressively propagates toward the ground surface. Surface subsidence may continue not only during active exploitation but also for extended periods after mining operations have ceased, generating delayed deformation phenomena that may persist for decades [1–4].

The magnitude and temporal evolution of mining-induced ground deformation are controlled by multiple factors, including mining depth, extraction geometry, panel dimensions, lithological heterogeneity, mechanical properties of surrounding formations, and the long-term rheological behavior of sedimentary rocks [5,6].

In underground coal basins characterized by stratified sedimentary successions, delayed post-mining subsidence often develops gradually through secondary compaction processes, progressive redistribution of internal stresses, and slow mechanical readjustment of residual underground voids.

Numerous studies have documented the relationship between underground coal extraction and the development of surface subsidence. Classical subsidence theories proposed by the National Coal Board [7], Peng [1], and Whittaker and Reddish [2] established the geomechanical framework describing deformation propagation from underground excavations to the ground surface. More recent studies have demonstrated that post-mining deformation may remain active for long periods after mining reduction or closure, particularly in geological environments characterized by plastic formations such as clays, marls, and weak sedimentary sequences.

Long-term monitoring of mining-induced deformation remains essential for understanding the persistence of residual geomechanical hazards in former mining regions. Traditional monitoring techniques have increasingly been complemented by modern geodetic technologies, particularly GNSS, which allow highly accurate multi-temporal assessment of three-dimensional displacement over extended observation periods [8].

Recent studies increasingly combine GNSS monitoring, InSAR observations, and integrated satellite- and ground-based geodetic approaches to improve the detection of long-term mining-induced deformation processes in active and abandoned mining areas [4,8–10].

The Jiu Valley Coal Basin, located in southwestern Romania, represents one of the most important historical underground coal mining districts in Eastern Europe. Decades of intensive underground exploitation have significantly altered the mechanical equilibrium of the geological structure, generating widespread deformation phenomena that continue to affect surface stability. Despite the long mining history of this region, relatively limited research has focused on evaluating the long-term persistence of post-mining subsidence using modern high-precision geodetic monitoring techniques.

The present study investigates the long-term evolution of mining-induced surface deformation in the Maleia sector, located within the Livezeni underground mining perimeter of the Jiu Valley Coal Basin. A historical geodetic monitoring network initially established in 2006 was reoccupied and remeasured using GNSS technology in 2026. By comparing contemporary measurements with historical observations acquired in 2007, this study evaluates nineteen years of cumulative ground deformation and provides new empirical evidence regarding delayed mining-induced subsidence persistence in post-exploitation underground coal mining environments.

Unlike most previous studies focused primarily on active mining periods, the present research provides one of the few long-term GNSS field datasets documenting delayed mining-induced subsidence over a nineteen-year observation interval in an underground coal basin. This study contributes new empirical evidence regarding the long-term geomechanical evolution of post-exploitation mining environments in Eastern Europe, where comparable field observations remain relatively scarce.

Recent advances in satellite-based deformation monitoring techniques, particularly multi-temporal InSAR approaches, have significantly improved the capability to detect long-term mining-induced ground deformation over large post-mining areas [10–13].

Beyond quantifying historical ground deformation, the long-term monitoring presented in this study provides essential information for post-mining hazard assessment, supports evidence-based land-use planning, and establishes a valuable reference dataset for future predictive geomechanical modelling.

Figure 1 illustrates the spatial distribution of the historical geodetic monitoring network and the underground mining galleries within the Maleia sector of the Livezeni underground coal mine, Jiu Valley Basin, Romania.

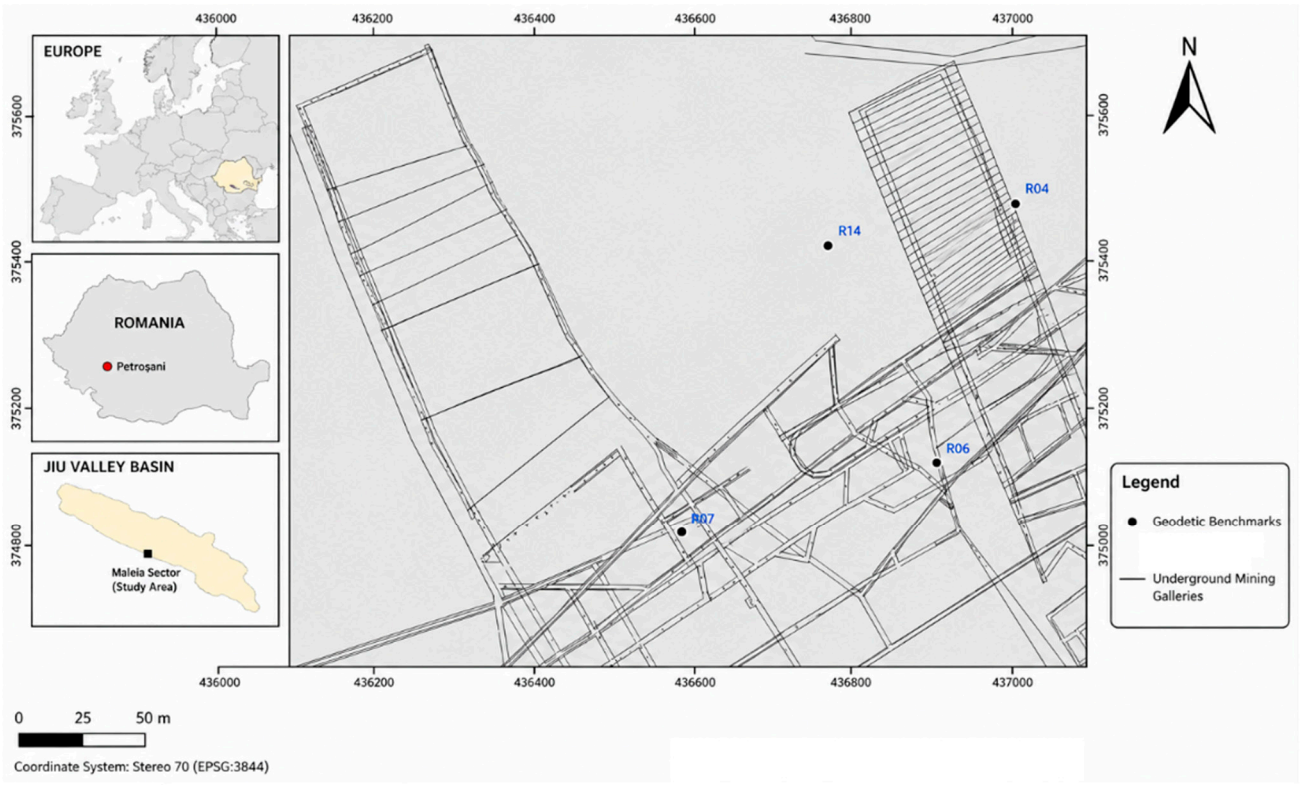


Figure 1. Spatial distribution of the historical geodetic monitoring network and underground mining galleries within the Maleia sector of the Livezeni underground coal mine, Jiu Valley Basin, Romania.

2. Geological Setting and Study Area

The study area is located within the Jiu Valley Coal Basin, situated in the Southern Carpathians of Romania, one of the most important historical underground coal mining regions in Eastern Europe. The basin has been intensively exploited for hard coal extraction for more than a century and represents a complex geological environment where prolonged underground mining activities have significantly altered the natural geomechanical equilibrium of the rock mass.

From a geological perspective, the Petroșani Basin is characterized by a complex sedimentary succession developed primarily during the Upper Carboniferous and overlain locally by Neogene and Quaternary deposits. The coal-bearing formations consist predominantly of alternating sequences of sandstones, claystones, marls, conglomerates, and multiple economically exploitable coal seams. The stratigraphic structure presents strong lithological heterogeneity, which directly controls the mechanical response of the overlying rock mass to underground excavation processes.

The present research focuses on the Maleia sector, located within the underground mining perimeter of the Livezeni Mine, one of the major coal extraction units historically operating in the eastern sector of the Jiu Valley Basin. Mining activities in this sector were primarily concentrated on Coal Seam No. 3, a relatively thick coal seam extensively exploited using underground extraction methods based on controlled roof collapse techniques.

Progressive underground extraction using caving methods significantly modified the stress distribution within the surrounding geological structure, generating mechanical instability zones and inducing deformation processes that propagated vertically toward the surface. As underground voids developed, the overlying sedimentary formations gradually underwent structural readjustment processes controlled by both the geometry of the excavated panels and the geomechanical behavior of surrounding lithological units.

A key geological characteristic of the study area is the presence of clay-rich and marl-rich sedimentary sequences, which exhibit significant plastic behavior under long-term mechanical loading conditions. These formations favor progressive rheological deformation, delayed compaction processes, and prolonged redistribution of internal stresses, contributing directly to the persistence of delayed mining-induced subsidence observed long after the reduction in or cessation of active mining operations [3,14].

Weak sedimentary formations such as claystones and marls are widely recognized for their susceptibility to progressive creep deformation and delayed consolidation under long-term stress redistribution conditions [6,15].

The Maleia sector represents an ideal natural laboratory for long-term deformation analysis due to the existence of historical underground mining documentation, geological records, and a permanent geodetic monitoring network established during previous subsidence investigations. The availability of historical and contemporary geodetic measurements over an extended nineteen-year observation interval provides a rare opportunity to evaluate the long-term evolution of residual ground deformation in a post-mining geological environment.

Understanding the geological controls governing subsidence development in the Jiu Valley Basin is essential for interpreting the long-term deformation patterns identified in the present study. The geological setting provides the basis for explaining the spatial variability of cumulative subsidence, particularly the localized deformation maximum observed at benchmark R14, where mining geometry and lithological conditions jointly controlled the long-term geomechanical response of the overlying rock mass.

Table 1 summarizes the characteristics of the monitoring network used in this study.

Table 1. Monitoring Network Characteristics.

Parameter	Value
Number of benchmarks	17
Study area	Maleia Sector—Livezeni Mine
Observation campaigns	2007, 2026
Coordinate system	Stereo 70
Measurement technology	GNSS
Observation interval	19 years

The spatial relationship between the monitoring network, underground mining galleries, exploited mining panels, and the cadastral property is shown in Figure 2.

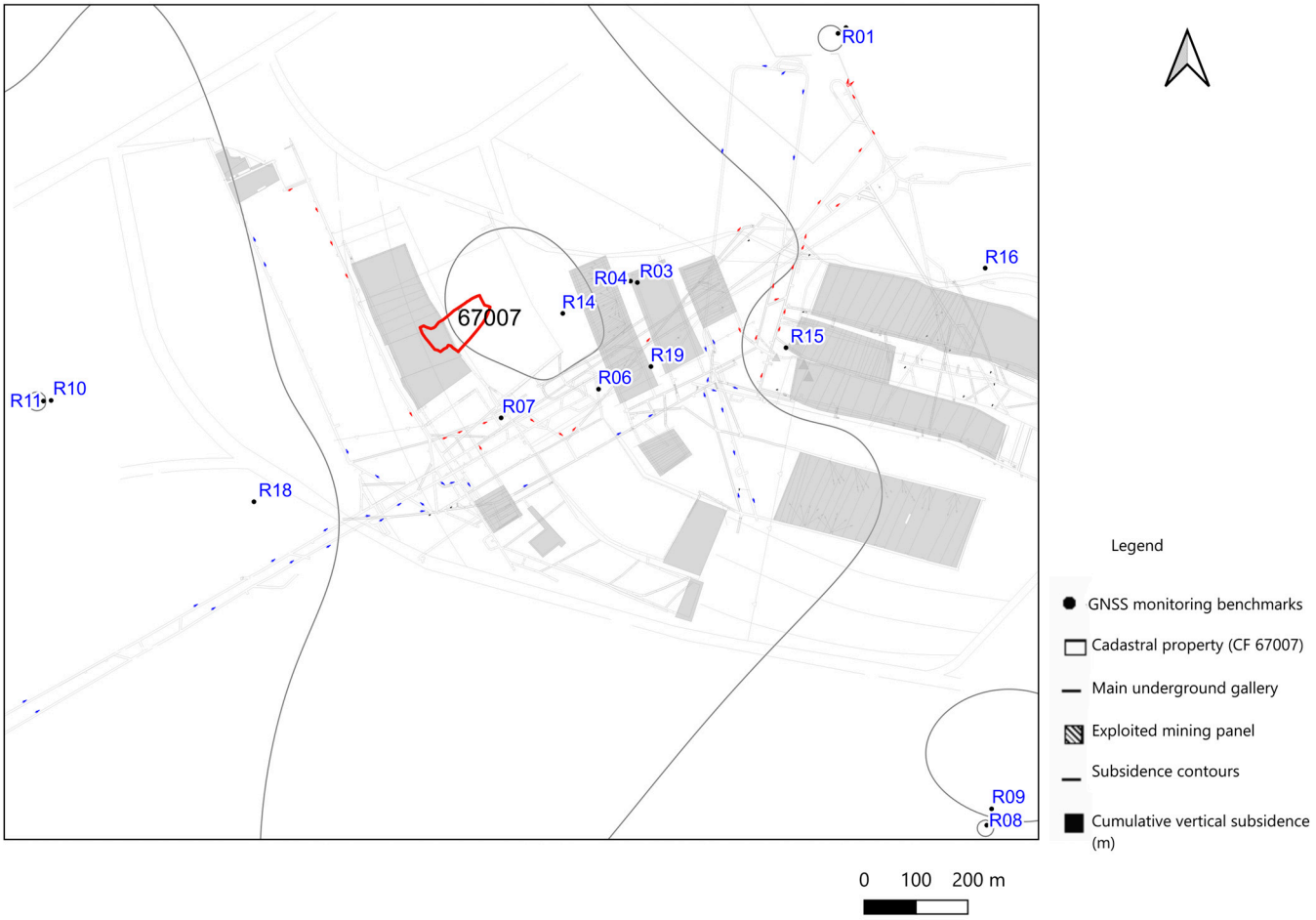


Figure 2. Spatial relationship between the interpolated cumulative vertical subsidence field (2007–2026), the underground mining galleries, exploited panels, and the cadastral property CF 67007 in the Maleia sector. Black contour lines represent the interpolated subsidence contours derived from GNSS measurements, while the grey polygons indicate the exploited underground mining panels. The complete GNSS monitoring network is shown, highlighting the location of benchmark R14, where the maximum cumulative vertical displacement (−3.853 m) was recorded.

3. Materials and Methods

3.1. Geodetic Monitoring Network

The geodetic monitoring network analyzed in this study was originally established in 2006 as part of a national Romanian research project focused on evaluating land subsidence processes induced by underground mining activities in the Petroșani Coal Basin. The original monitoring system established in 2006 consisted of forty permanent benchmarks distributed within and around the mining area. While most benchmarks were installed inside the mining-affected zone to monitor ground deformation, several reference benchmarks were deliberately located outside the mining perimeter and were considered stable control points because they were beyond the expected zone of mining influence.

For the present study, seventeen representative benchmarks located within the Maleia sector, corresponding to the underground exploitation perimeter of the Livezeni Mine, were selected for long-term deformation analysis. These benchmarks were selected because they are located directly above historically exploited underground extraction panels and therefore provide representative conditions for evaluating long-term deformation evolution.

The seventeen selected benchmarks provide a unique long-term observation framework for directly comparing historical (2007) and contemporary (2026) measurements over a nineteen-year interval. These benchmarks are distributed above different historical un-

derground extraction panels, allowing evaluation of the spatial variability of post-mining deformation. Although the original monitoring network established in 2006 comprised forty permanent benchmarks, only seventeen remained identifiable and suitable for re-occupation during the 2026 survey because the others had been destroyed, displaced, or become inaccessible due to natural degradation, land-use changes, and mining-related surface modifications over the two-decade interval. Consequently, the present analysis is based exclusively on these seventeen benchmarks, allowing for direct comparison between the historical (2007) and contemporary (2026) observations. Reference benchmarks located outside the mining perimeter were considered stable and served as control points for the geodetic network adjustment.

The monitoring network was referenced to stable control points located outside the mining influence zone. These control points were originally established with respect to the permanent GNSS reference station located in the Petroșani area, approximately 2 km from the monitoring network. The same reference framework was maintained for both the 2007 and 2026 observation campaigns, ensuring consistency between the two measurement epochs.

The reference benchmarks were therefore considered stable for the purpose of the deformation analysis based on their location outside the expected mining influence zone. However, their long-term stability was not independently assessed within the present study; consequently, stability is assumed on the basis of network design and site location rather than demonstrated through an independent long-term control analysis.

3.2. Historical and Contemporary Measurement Campaigns

The first reference dataset used in the present research corresponds to the geodetic monitoring campaign performed in October 2007, during which the coordinates of the monitoring benchmarks were determined using high-precision geodetic surveying techniques within the Romanian national coordinate reference system Stereo 70.

A new geodetic survey campaign was conducted in March 2026 in order to reoccupy the historical monitoring benchmarks and determine their updated three-dimensional spatial coordinates. The measurements were performed using Leica GS18T dual-frequency GNSS receivers (Leica Geosystems AG, Heerbrugg, Switzerland) receivers operating in static differential positioning mode. Each benchmark was continuously observed for approximately 20 to 30 min, allowing sufficient satellite redundancy and stable satellite constellation geometry during the observation sessions.

Raw GNSS observations were post-processed using Leica Infinity v4.0 (Leica Geosystems AG, Heerbrugg, Switzerland) through differential correction with respect to the Romanian national geodetic reference framework. All coordinates were referenced to the Stereo 70 national projection system, while elevations were expressed in the Black Sea 1975 vertical datum. Stable satellite geometry (acceptable PDOP values) and repeated static observations ensured centimeter-level positioning accuracy, which is fully adequate for detecting the meter-scale cumulative subsidence observed in this study. High-precision GNSS monitoring is widely recognized as one of the most reliable techniques for detecting millimeter- to centimeter-scale ground deformation in engineering geology and geodynamic investigations [16–18].

The monitoring network was adjusted using the stable reference benchmarks located outside the mining influence zone, ensuring consistency between the historical and contemporary coordinate datasets. The spatial distribution of cumulative vertical subsidence derived from IDW interpolation is presented in Figure 3.

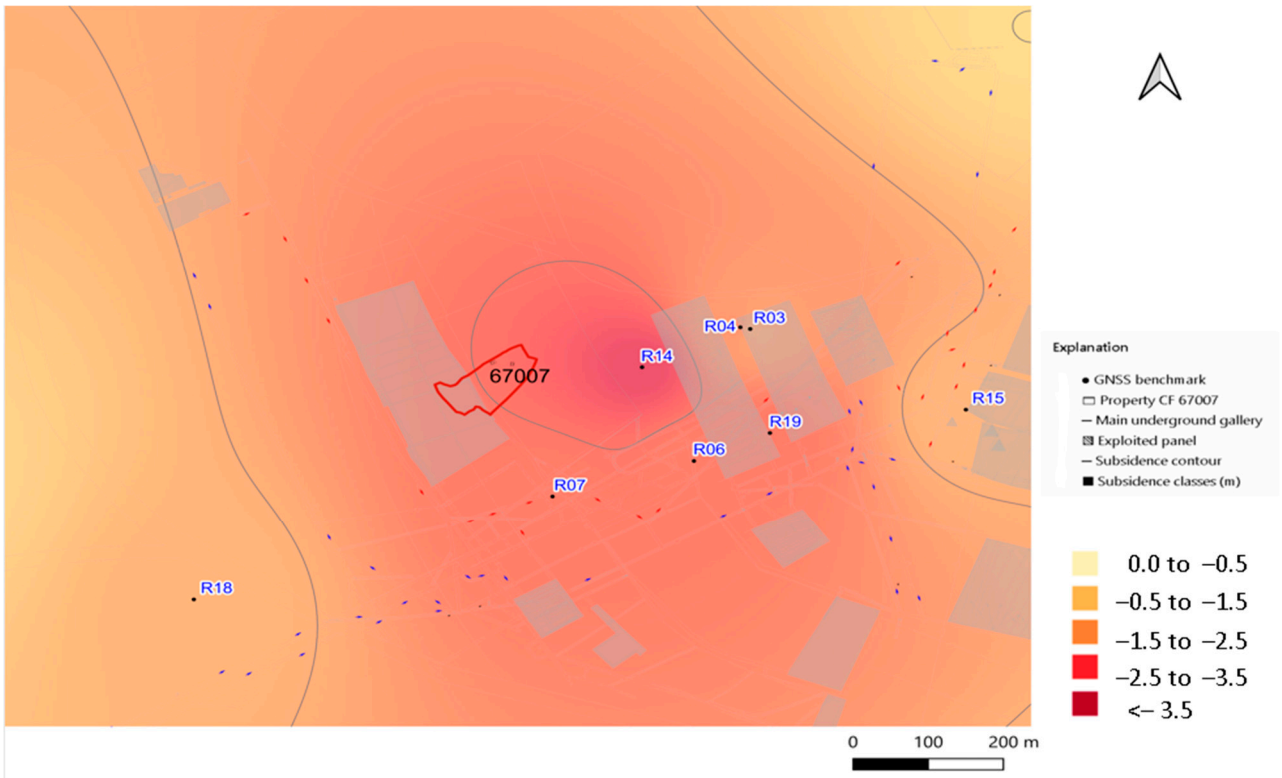


Figure 3. Spatial distribution of cumulative vertical subsidence in the Maleia sector derived from inverse distance weighting (IDW) interpolation of GNSS measurements acquired between 2007 and 2026. The figure illustrates the interpolated deformation surface together with the corresponding subsidence classes and contour lines used for spatial interpretation.

3.3. Accuracy Assessment

In order to ensure data reliability, repeated static GNSS observations were performed at each benchmark during the 2026 survey campaign. The available 2026 GNSS records report fixed solutions and include point-specific quality indicators such as PDOP, satellite counts, and estimated standard deviations for the horizontal and vertical components. These records generally indicate centimetre- to sub-centimetre-level internal precision, although individual observations showed lower precision.

Repeated static observations were performed at each benchmark to assess measurement consistency. The estimated vertical positioning accuracy remained at the centimeter level, whereas the observed cumulative subsidence ranged from 0.082 m to 3.853 m. Consequently, the available 2026 precision indicators are small relative to the magnitude of the largest observed cumulative displacements, supporting the interpretation that these changes primarily reflect real ground deformation rather than contemporary instrumental uncertainty.

Although complete variance–covariance information from the historical 2007 campaign is no longer available, repeated observations during the 2026 campaign confirmed centimetre-level positioning consistency, which is fully adequate for detecting the observed metre-scale cumulative deformation.

3.4. Deformation Analysis Methodology

Ground deformation analysis was based on direct comparison of the benchmark coordinates determined during the historical campaign (2007) and those obtained during the GNSS survey conducted in 2026. Vertical displacement analysis was limited to the vertical component because mining-induced subsidence primarily manifests through long-

term downward ground deformation generated by underground void redistribution and progressive roof collapse processes.

The cumulative vertical displacement for each monitoring point was calculated using the standard relationship:

$$\Delta_Z = Z_{2026} - Z_{2007} \quad (1)$$

where:

- Δ_Z represents cumulative vertical displacement (m);
- Z_{2026} is the elevation measured during the 2026 GNSS survey;
- Z_{2007} is the historical elevation measured during the 2007 survey.

To evaluate the long-term deformation rate, the average annual subsidence rate was calculated using:

$$V_z = \frac{\Delta Z}{\Delta t} \quad (2)$$

where:

- V_z = is the average annual subsidence rate (m/year);
- Δt = is the observation interval (19 years).

The interpolation procedure follows the standard inverse distance weighting equation:

$$Z_{(x)} = \frac{\sum_{i=1}^{n} w_i Z_i}{\sum_{i=1}^{n} w_i} \quad (3)$$

where:

- $Z_{(x)}$ = is the interpolated subsidence value at location x;
- Z_i = is the observed subsidence value at sample point i;
- w_i = is the inverse-distance weight assigned to sample point i;
- n = is the total number of neighboring observations used in the interpolation.

The inverse-distance weights were computed according to:

$$w_i = \frac{1}{d_i^p} \quad (4)$$

where:

- d_i = distance between prediction location and sample point i;
- p = power parameter (typically $p = 2$);
- w_i = inverse-distance weight.

3.5. Spatial Interpolation Method

Spatial interpolation of cumulative subsidence values was performed using the Inverse Distance Weighting (IDW) method, widely applied for continuous surface modeling of spatially distributed environmental datasets [19–21].

Spatial interpolation was performed using the Inverse Distance Weighting (IDW) method because the monitoring network consisted of only seventeen observation points, which is generally considered insufficient for reliable variogram modeling required by ordinary kriging. IDW provides a robust deterministic interpolation that preserves local deformation anomalies without introducing assumptions regarding spatial stationarity or covariance structure. Since the primary objective of this study was to visualize the spatial distribution of measured mining-induced subsidence rather than to model spatial uncertainty, IDW was considered the most appropriate interpolation method for the available dataset. Furthermore, mining-induced deformation is characterized by localized subsi-

dence centers associated with underground extraction geometry, which are better preserved using IDW than by the smoothing effects commonly produced by kriging interpolation.

Several comparative studies have shown that deterministic interpolation methods often provide more stable results than kriging when spatial datasets contain limited observations and irregular sampling geometry [22].

Although the number of observation points is limited, the present dataset represents a rare long-term field monitoring record extending over nineteen years, which provides valuable empirical evidence regarding delayed subsidence persistence.

A power parameter of 3 was applied during interpolation, representing the standard weighting configuration commonly used for localized deformation modeling.

The overall methodological workflow consisted of four consecutive stages: (i) reoccupation of the historical monitoring network using static GNSS observations; (ii) differential post-processing of geodetic data; (iii) computation of cumulative and annual vertical displacements; and (iv) spatial interpolation and three-dimensional visualization of the resulting deformation field.

Given the limited number of monitoring benchmarks, no formal interpolation uncertainty assessment or cross-validation was performed; therefore, the IDW surface is used exclusively to visualize the spatial pattern of the measured subsidence values and should not be interpreted as a predictive deformation model.

4. Results

4.1. Vertical Displacement Analysis

Comparative analysis of the geodetic measurements performed in October 2007 and March 2026 revealed persistent vertical ground deformation affecting all seventeen monitored benchmarks within the investigated mining sector. The results indicate a consistent negative displacement trend, confirming that mining-induced subsidence remains an active long-term geomechanical process in the studied post-exploitation environment.

The calculated cumulative vertical displacements (ΔZ) ranged from a minimum value of -0.082 m recorded at benchmark R09 to a maximum value of -3.853 m observed at benchmark R14. The mean cumulative subsidence value calculated for the entire monitoring network reached -1.919 m, demonstrating significant long-term deformation affecting the investigated sector.

The highest cumulative subsidence values were concentrated within a limited group of benchmarks located above the historically most intensively exploited underground panels. This spatial concentration indicates that delayed deformation is not uniformly distributed across the monitoring network but is instead controlled by local geological conditions and underground mining geometry.

The fact that all monitoring benchmarks recorded negative vertical displacement values indicates that the geological system has not yet reached complete geomechanical equilibrium despite the significant reduction in active mining operations in the area.

4.2. Annual Subsidence Rate Assessment

To evaluate the temporal persistence of the deformation process, average annual subsidence rates were calculated for each benchmark over the nineteen-year observation interval.

Average annual subsidence rates provide a normalized representation of the cumulative deformation observed between the 2007 and 2026 measurement epochs. The highest rates were recorded in the central part of the monitoring network, whereas peripheral benchmarks generally exhibited lower values. This spatial pattern further supports the interpretation that long-term subsidence is primarily controlled by the geometry of historical

underground excavations and local geological conditions rather than by a uniform regional settlement process.

Although the absolute annual displacement values appear moderate, their persistence over a nineteen-year interval demonstrates that delayed post-mining subsidence remains an active long-term geological process capable of producing significant cumulative deformation over extended time periods.

The reported annual subsidence rates represent average values calculated over the nineteen-year observation interval and are presented exclusively for comparative purposes between monitoring benchmarks. They should not be interpreted as reflecting temporal variations or continuous deformation rates.

4.3. Spatial Distribution of Deformation Patterns

Spatial distribution analysis revealed a clearly non-uniform pattern of ground deformation throughout the investigated sector. The highest subsidence values were concentrated within a central deformation zone corresponding spatially with historical underground exploitation panels associated with Coal Seam No. 3.

The concentration of high subsidence values around benchmark R14 indicates the existence of a localized critical deformation sector where underground extraction geometry likely produced extensive residual voids and long-term progressive compaction processes.

To better visualize the three-dimensional geometry of the deformation field, a digital elevation model representing cumulative vertical subsidence was reconstructed using spatial interpolation of measured GNSS displacement values.

The resulting three-dimensional surface model reveals a clearly developed subsidence depression centered around benchmark R14, confirming the existence of a localized delayed deformation trough associated with the historical underground mining geometry. The reconstructed morphology highlights the asymmetric spatial behavior of long-term post-mining subsidence and provides additional evidence regarding the persistence of residual geomechanical instability within the investigated sector.

The relatively high coefficient of variation (50%) further confirms the significant spatial heterogeneity of subsidence development across the investigated monitoring network.

To better characterize the geometry of the observed deformation process, a longitudinal subsidence profile was reconstructed along the main monitoring transect crossing the central underground mining sector (R07–R06–R14–R04–R03).

The resulting profile reveals a clearly defined subsidence trough geometry, with the maximum cumulative vertical displacement recorded at benchmark R14 (−3.853 m), located above the historically most intensively exploited underground panel. The asymmetric deformation pattern suggests that delayed post-mining subsidence remains strongly controlled by the geometry of historical underground excavations and progressive long-term compaction processes within the overlying sedimentary sequence.

The model highlights the main subsidence depression centered around benchmark R14, representing the sector affected by maximum delayed post-mining deformation.

Although the monitoring network includes a relatively limited number of benchmarks, the available dataset represents one of the few long-term field observations documenting delayed post-mining subsidence behavior over nearly two decades within a closed underground mining environment.

The three-dimensional reconstruction complements the quantitative analysis by illustrating the morphology of the subsidence basin and emphasizing the localized character of the delayed deformation field. The cumulative vertical subsidence is illustrated from multiple perspectives in Figure 4, including the plan view, three-dimensional reconstruction, and W–E cross-sectional profile.

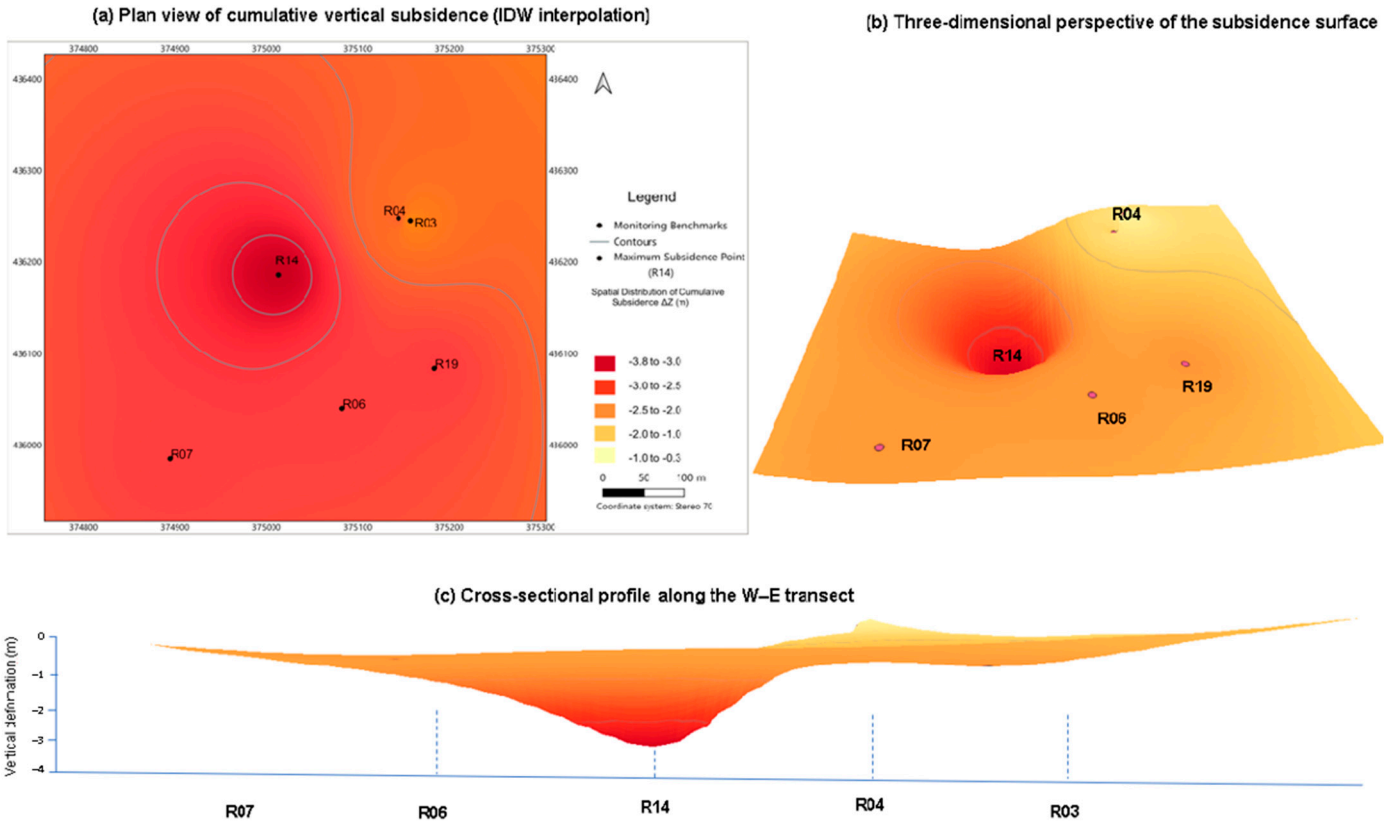


Figure 4. Multi-perspective representation of cumulative vertical subsidence in the Maleia sector derived from GNSS measurements acquired between 2007 and 2026: (**a**) plan-view IDW interpolation with contour lines and GNSS benchmarks; (**b**) three-dimensional reconstruction of the subsidence basin highlighting the maximum cumulative subsidence at benchmark R14; (**c**) W–E cross-sectional profile illustrating the geometry of the subsidence trough.

4.4. Evidence of Persistent Delayed Subsidence

One of the most significant findings of the present study is the demonstration that measurable subsidence remains active nearly two decades after the main underground mining activities were substantially reduced. The persistence of negative vertical displacement values recorded at every monitored benchmark provides strong empirical evidence supporting the existence of delayed mining-induced subsidence processes operating over extended post-exploitation timescales.

These results suggest that underground void redistribution, secondary compaction mechanisms, and long-term rheological adjustment of weak sedimentary formations continue to influence ground stability well beyond the active mining phase.

Table 2 summarizes the measured vertical displacements and the average annual subsidence rates at the monitoring benchmarks between 2007 and 2026.

Together, these observations demonstrate that the investigated mining area has not yet reached complete geomechanical equilibrium. Instead, delayed subsidence continues to develop through long-term stress redistribution, progressive compaction of underground voids, and rheological adjustment of weak sedimentary formations. A statistical summary of the measured vertical subsidence values is presented in Table 3.

The relatively high coefficient of variation indicates considerable spatial heterogeneity of subsidence development, supporting the interpretation of localized deformation centers rather than uniform regional settlement. Figure 5 compares the cumulative vertical displacement measured at the individual monitoring benchmarks during the 2007–2026 observation period.

Table 2. Measured Vertical Displacements and Average Annual Subsidence Rates at the Monitoring Benchmarks (2007–2026).

Benchmarks	*Z* 2007 (m)	*Z* 2026 (m)	Δ*Z* (m)	V_z (m/Year)
R01	754.491	753.550	−0.941	−0.050
R02	753.209	752.030	−1.179	−0.062
R03	825.637	823.570	−2.067	−0.109
R04	824.897	822.439	−2.458	−0.129
R06	774.209	771.361	−2.848	−0.150
R07	754.029	751.169	−2.860	−0.151
R08	826.989	824.862	−2.127	−0.112
R09	825.555	825.473	−0.082	−0.004
R10	650.951	649.621	−1.330	−0.070
R11	649.210	648.310	−0.900	−0.047
R12	688.355	685.799	−2.556	−0.135
R13	680.893	679.398	−1.495	−0.079
R14	807.401	803.548	−3.853	−0.203
R15	831.867	830.017	−1.850	−0.097
R16	777.103	775.797	−1.306	−0.069
R18	677.504	675.627	−1.877	−0.099
R19	787.334	784.458	−2.876	−0.151

Table 3. Statistical Summary of Vertical Subsidence.

Parameter	Value
Number of benchmarks	17
Maximum subsidence	−3.853 m
Minimum subsidence	−0.082 m
Mean subsidence	−1.919 m
Median subsidence	−1.877 m
Standard deviation	0.960 m
Coefficient of variation	50.00%

Figure 6 illustrates the longitudinal subsidence profile across the main monitoring transect.

The profile highlights a well-defined subsidence trough geometry, with maximum cumulative vertical displacement recorded at benchmark R14, corresponding to the most geomechanically unstable zone above the historically exploited underground panel.

In order to further examine the spatial behavior of delayed subsidence, the horizontal distance between the critical deformation center identified at benchmark R14 and adjacent monitoring benchmarks located along the main deformation transect was evaluated.

A comparative analysis of benchmark displacements indicates that subsidence magnitude does not decrease linearly with increasing distance from the principal deformation center identified at benchmark R14. For instance, benchmark R07, located approximately 233.7 m from the critical subsidence center, recorded a cumulative vertical displacement of −2.860 m, exceeding deformation values measured at closer benchmarks such as R03 and R04. This non-linear spatial behavior suggests that delayed post-mining subsidence is controlled not only by geometric proximity to the subsidence center but also by the spatial configuration of historical underground excavations and the heterogeneous geomechanical response of the overlying sedimentary sequence.

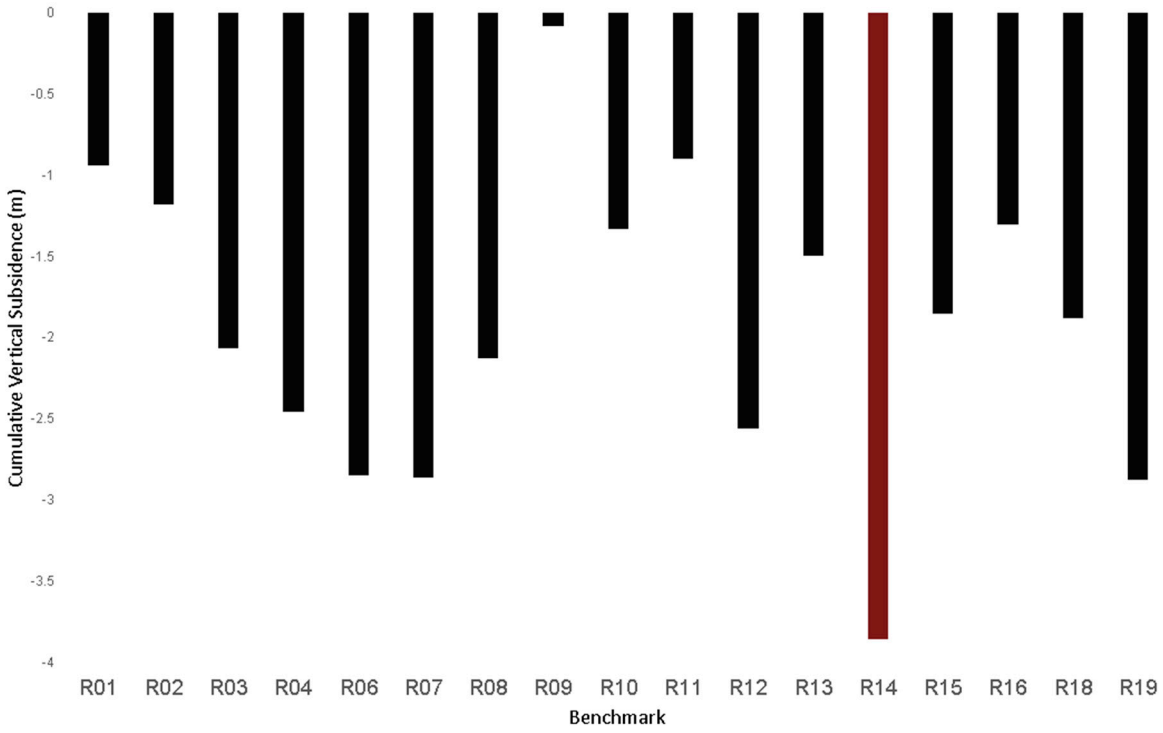


Figure 5. Comparative vertical displacement recorded at individual monitoring benchmarks over the 2007–2026 observation period. Benchmark R14 is highlighted in red because it recorded the maximum cumulative subsidence value within the monitoring network.

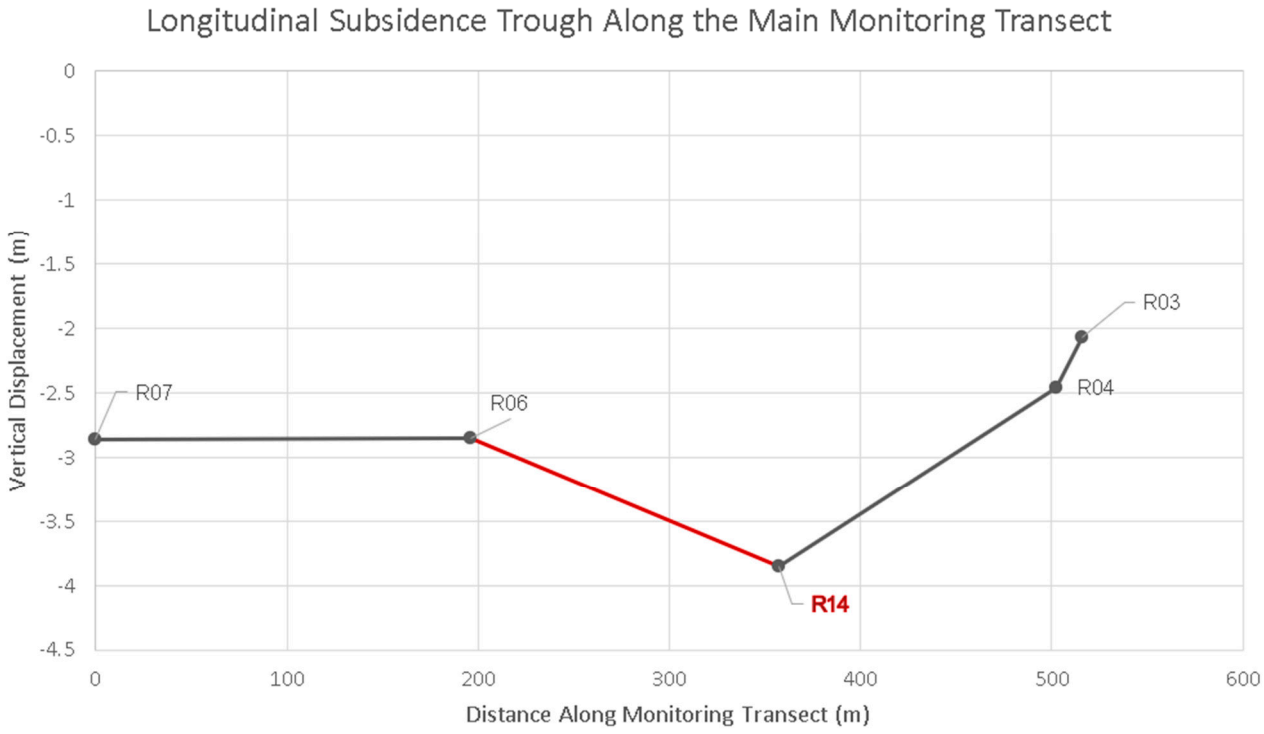


Figure 6. Longitudinal subsidence profile reconstructed along the principal monitoring transect crossing the central underground mining sector. The red segment highlights the section of the profile corresponding to the maximum cumulative subsidence centered at benchmark R14.

5. Discussion

The present study demonstrates that measurable mining-induced subsidence may persist for at least nineteen years after the reduction in underground coal extraction in the investigated sector of the Jiu Valley Coal Basin. This finding indicates that the post-mining geological system has not yet reached complete geomechanical equilibrium and continues to evolve through delayed stress redistribution and progressive compaction processes. Although the classical subsidence models proposed by Peng [1] and Whittaker and Reddish [2] primarily describe deformation during active mining, more recent investigations have demonstrated that residual ground movements may continue for years or even decades after mine closure [4,23–25].

Comparable long-term post-mining deformation behavior has been documented in several former underground coal basins worldwide. Studies conducted in Upper Silesia (Poland), Ruhr Basin (Germany), and multiple Chinese coal districts have demonstrated that measurable residual subsidence may persist for years or even decades after mining cessation, particularly in geological environments characterized by heterogeneous sedimentary formations and progressive rheological compaction mechanisms [4,14,23].

Recent research based on time-series InSAR monitoring has further demonstrated that residual deformation may continue for extended periods after mine closure, particularly in coal basins characterized by heterogeneous geological structures and delayed rheological compaction processes [24,25].

Similar long-term residual deformation behavior has also been observed in abandoned coal mining districts in the Czech Republic, where delayed subsidence persisted for more than ten years after mine closure due to progressive compaction of residual underground voids [26].

A fundamental factor explaining the persistence of deformation in the investigated area is the geological composition of the Petroșani Basin.

The sedimentary succession is characterized by alternating sequences of competent sandstone formations interbedded with mechanically weaker marl and clay-rich units. While competent lithologies may temporarily redistribute mechanical stresses through arching effects, weak plastic formations remain susceptible to long-term rheological deformation and progressive secondary compaction.

The delayed closure of these underground cavities may continue to induce secondary compaction processes responsible for prolonged vertical surface deformation. Similar deformation mechanisms associated with underground excavation geometry have also been documented by Singh and Dhar [27] and Brady and Brown [6]. This observation suggests that delayed subsidence processes remain strongly dependent on historical underground excavation geometry, even after prolonged post-exploitation periods exceeding two decades.

The significantly higher subsidence recorded at benchmark R14 likely reflects the combined influence of underground extraction geometry and local geological conditions. Historical mining plans indicate that this sector was positioned above one of the most intensively exploited underground panels, where progressive roof collapse mechanisms probably generated larger residual underground voids. In addition, the local lithological succession dominated by clay-rich and marl-rich formations may favor long-term rheological compaction processes, prolonging delayed subsidence well beyond the active mining period.

From an engineering geology perspective, the observed deformation pattern demonstrates that former underground mining areas should not automatically be considered geomechanically stable after mine closure. Residual deformation may continue for prolonged periods owing to delayed stress redistribution and progressive compaction of

partially collapsed underground excavations, representing a persistent geological hazard for infrastructure development and future land-use planning.

Post-mining hazard assessment increasingly requires integration of geotechnical monitoring, remote sensing observations, and predictive numerical modeling in order to identify long-term instability zones affecting future land-use planning [4,23].

Such integrated approaches would improve both the interpretation of long-term deformation mechanisms and the predictive capability of post-mining hazard assessment.

These results have important implications for land-use planning and infrastructure management in former mining regions. Areas affected by long-term residual subsidence may require continued geotechnical monitoring prior to future urban development, construction activities, or land rehabilitation programs.

Beyond its implications for the investigated mining area, the methodological framework presented in this study may also be applied to other abandoned underground coal basins where historical geodetic measurements are available. The integration of repeated GNSS observations, spatial interpolation, and geological interpretation provides a practical approach for evaluating the long-term evolution of residual mining-induced deformation and supporting post-mining hazard assessment.

The long temporal dataset analyzed in this study contributes valuable empirical evidence supporting the hypothesis that delayed mining-induced subsidence represents a persistent post-exploitation geological process controlled by both underground mining geometry and the long-term rheological behavior of sedimentary formations. These findings highlight the necessity of implementing extended geodetic monitoring programs in historical underground mining regions where residual geomechanical instability may remain undetected for decades.

To the best of the authors' knowledge, few field-based studies have documented direct GNSS-derived subsidence evolution over observation intervals approaching two decades in post-mining underground coal environments.

These findings demonstrate that delayed mining-induced subsidence should be considered an active long-term geological hazard requiring extended monitoring strategies in former underground mining regions affected by historical coal exploitation.

The cumulative subsidence values observed in the present study exceed deformation magnitudes reported in several European post-mining environments. For example, Blachowski et al. [23] reported post-mining residual deformation generally below 1 m in abandoned coal basins in Poland, whereas cumulative vertical displacements exceeding 3.8 m were recorded in the present study. Similar long-term residual deformation has also been documented in other European post-mining districts, including the Ostrava–Karviná Coalfield in the Czech Republic [26] and additional coal basins investigated by Blachowski et al. [23]. These comparisons indicate that delayed post-mining subsidence is a widespread phenomenon, while its magnitude and persistence are strongly controlled by geological structure, underground extraction geometry, and the long-term rheological behavior of weak sedimentary formations.

The results obtained in this study may support decision-making processes related to post-mining land management and infrastructure safety. Long-term deformation monitoring provides valuable information that can complement national regulatory frameworks governing the assessment and management of mining-affected areas. Although the present study does not evaluate regulatory compliance or propose engineering mitigation measures, the generated deformation dataset constitutes an important source of information for future risk assessment and land-use planning.

Study Limitations

The present study presents several limitations that should be considered when interpreting the obtained results. The deformation analysis is based on two discrete measurement epochs separated by a nineteen-year interval, limiting the possibility of reconstructing intermediate temporal variations in subsidence acceleration or deceleration. In addition, the relatively limited number of preserved monitoring benchmarks restricts the spatial resolution of the interpolation model. Future studies integrating continuous GNSS monitoring, satellite InSAR observations, and numerical geomechanical modeling would improve the temporal and spatial characterization of delayed post-mining deformation processes. Such integrated approaches would also improve the predictive capability of post-mining deformation assessment and support long-term geomechanical hazard forecasting.

Although the observed deformation is interpreted in the context of historical underground coal mining, the primary objective of this study is the geodetic quantification and spatial analysis of long-term post-mining subsidence based on multi-temporal GNSS observations. A comprehensive geological or geomechanical assessment would require additional geological cross-sections, complete mining production records, and detailed geotechnical information, which were not available for the present study. Therefore, the geological interpretation presented herein should be regarded as supportive rather than exhaustive, while the results provide a quantitative basis for future multidisciplinary investigations involving geodesists, geologists, and mining engineers.

Figure 7 summarizes the conceptual mechanism responsible for the long-term persistence of mining-induced subsidence inferred from the present investigation. The diagram integrates the historical underground mining activity, progressive roof collapse, stress redistribution, delayed rheological compaction, and the resulting surface deformation observed between 2007 and 2026. This conceptual model synthesizes the principal geological processes controlling the evolution of delayed post-mining subsidence in the investigated sector.

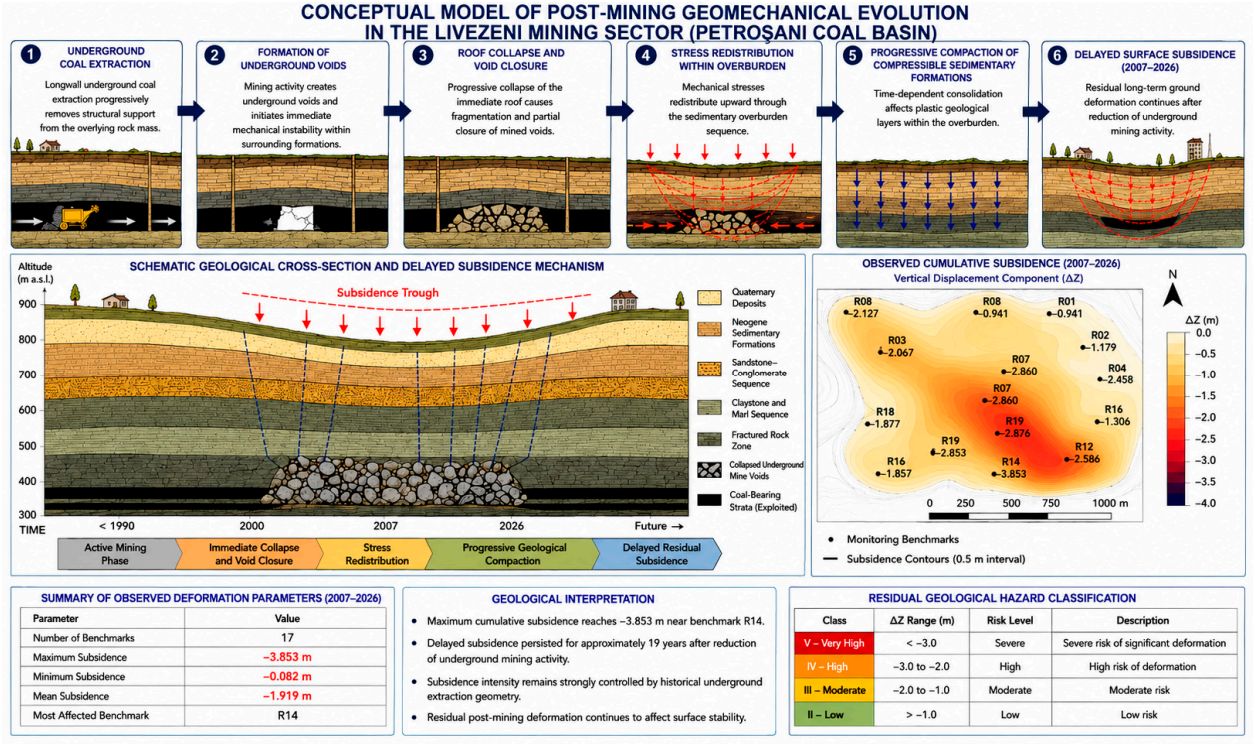


Figure 7. Conceptual model illustrating the long-term evolution of mining-induced subsidence after underground coal extraction, highlighting progressive roof collapse, stress redistribution, rheological

compaction of weak sedimentary formations, and the resulting delayed surface deformation observed between 2007 and 2026. Red arrows indicate downward surface displacement, the red dashed lines illustrate the progressive development of the subsidence trough associated with stress redistribution, and the blue dashed lines indicate the zone of deformation propagation above the exploited underground panels.

6. Conclusions

This study demonstrates that measurable mining-induced subsidence persists nearly two decades after the reduction in underground coal extraction in the Maleia sector of the Jiu Valley Coal Basin, Romania, using multi-temporal geodetic measurements acquired over a nineteen-year observation interval between 2007 and 2026.

Comparative analysis of seventeen permanent monitoring benchmarks demonstrated that measurable subsidence remains active throughout the investigated mining sector despite the significant reduction in underground coal extraction activities. All analyzed benchmarks recorded negative vertical displacement values, confirming the persistence of delayed post-mining deformation processes affecting the geological system long after the main extraction phase.

The results revealed cumulative vertical subsidence values ranging from −0.082 m to −3.853 m, with the maximum deformation recorded at benchmark R14. Average annual subsidence rates calculated over the nineteen-year observation interval reached values up to −0.203 m/year and are reported as normalized values for comparison between monitoring benchmarks.

The obtained results provide strong empirical evidence that post-mining geological systems may remain mechanically unstable over extended temporal intervals due to progressive secondary compaction of underground voids, delayed redistribution of internal stresses, and long-term rheological adjustment of weak sedimentary formations.

From an engineering geology perspective, the study demonstrates the importance of implementing long-term geodetic monitoring strategies in former underground mining environments in order to identify residual geomechanical hazards that may remain active decades after mine closure.

The findings contribute new long-term field evidence regarding delayed mining-induced subsidence behavior in sedimentary underground coal basins and improve current understanding of the long-term geomechanical evolution of post-exploitation mining environments.

The proposed monitoring strategy demonstrates the value of integrating repeated field observations with spatial analysis techniques for evaluating the long-term stability of former underground mining areas. Such approaches may support future geotechnical investigations, land-use planning, and risk management in post-mining environments.

Overall, the present study provides rare long-term field evidence demonstrating that mining-induced subsidence remains an active geological process nearly two decades after underground coal exploitation, emphasizing the importance of sustained geodetic monitoring in post-mining environments.

An important limitation of the present study is represented by the relatively limited number of historical monitoring benchmarks and the absence of continuous intermediate observations between the two measurement epochs, which restricts the possibility of reconstructing the full temporal evolution of subsidence acceleration or deceleration phases.

The results demonstrate that long-term GNSS monitoring is not only a tool for documenting past deformation but also an essential component of post-mining risk assessment and the sustainable management of former underground mining areas.

Future research should integrate continuous GNSS monitoring, multi-temporal satellite InSAR observations, and numerical geomechanical modeling approaches, which are increasingly applied in modern subsidence hazard assessment studies [8,11,12].

Author Contributions: Conceptualization, T.G. and C.P.; Methodology, T.G. and C.P.; Formal analysis, T.G.; Investigation, T.G.; Data curation, T.G.; Writing—original draft, T.G.; Writing—review & editing, T.G. and C.P.; Visualization, T.G.; Supervision, C.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The processed data supporting the findings of this study, as well as the underlying data necessary for scientific verification, can be made available by the corresponding author on a case-by-case basis upon reasonable request for scientific research purposes.

Acknowledgments: The authors gratefully acknowledge the historical geodetic monitoring datasets collected during previous subsidence monitoring investigations conducted in the Jiu Valley Coal Basin, which provided the essential baseline data for the long-term comparative deformation analysis presented in this study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Peng, S.S. *Surface Subsidence Engineering*; Society for Mining, Metallurgy and Exploration: Littleton, CO, USA, 1992.
2. Whittaker, B.N.; Reddish, D.J. *Subsidence: Occurrence, Prediction and Control*; Elsevier: Amsterdam, The Netherlands, 1989.
3. Bell, F.G.; Stacey, T.R.; Genske, D.D. Mining subsidence and its effect on the environment: Some differing examples. *Environ. Geol.* **2000**, *40*, 135–152. [CrossRef]
4. Cai, Y.; Zhang, X.; Liu, H.; Wang, J. A Review of Monitoring, Calculation, and Simulation Methods for Mining Subsidence. *Int. J. Coal Sci. Technol.* **2023**, *10*, 56. [CrossRef]
5. Kratzsch, H. *Mining Subsidence Engineering*; Springer: Berlin, Germany, 1983.
6. Brady, B.H.G.; Brown, E.T. *Rock Mechanics for Underground Mining*; Springer: Dordrecht, The Netherlands, 2004.
7. National Coal Board. *Subsidence Engineers Handbook*; National Coal Board Publishing: London, UK, 1975.
8. Bo, H.; Li, Y.; Tan, X.; Dong, Z.; Zheng, G.; Wang, Q.; Yu, K. Estimation of Ground Subsidence Deformation Induced by Underground Coal Mining with GNSS-IR. *Remote Sens.* **2023**, *15*, 96. [CrossRef]
9. Spreckels, V. Multisensor Monitoring of Ground Movements over Large Areas to Conduct the Change from the Active Underground Hard Coal Mining Ages to the Post-Mining Era. In *Proceedings of the 5th Joint International Symposium on Deformation Monitoring (JISDM 2022), Valencia, Spain, 20–22 June 2022*; Editorial Universitat Politècnica de València: Valencia, Spain, 2023; pp. 637–644.
10. Ma, Z.; Liu, Y.; Chen, H.; Wang, T. Life Cycle Mining Deformation Monitoring and Analysis Using Time-Series InSAR. *Remote Sens.* **2024**, *16*, 2335. [CrossRef]
11. Ferretti, A.; Prati, C.; Rocca, F. Permanent Scatterers in SAR Interferometry. *IEEE Trans. Geosci. Remote Sens.* **2001**, *39*, 8–20. [CrossRef]
12. Hooper, A.; Segall, P.; Zebker, H.A. Persistent Scatterer Interferometric Synthetic Aperture Radar for Crustal Deformation Analysis, with Application to Volcán Alcedo, Galápagos. *J. Geophys. Res. Solid Earth* **2007**, *112*, B07407. [CrossRef]
13. Herrera, G.; Tomás, R.; López-Sánchez, J.M.; Delgado, J.; Mallorquí, J.J.; Duque, S.; Mulas, J. Advanced DInSAR Analysis on Mining Areas: La Unión Case Study (SE Spain). *Eng. Geol.* **2007**, *90*, 148–159. [CrossRef]
14. Strozik, G.; Jendruś, R.; Manowska, A.; Popczyk, M. Mine Subsidence as a Post-Mining Effect in the Upper Silesia Coal Basin. *Pol. J. Environ. Stud.* **2016**, *25*, 1011–1020. [CrossRef] [PubMed]
15. Bieniawski, Z.T. *Engineering Rock Mass Classifications*; John Wiley & Sons: New York, NY, USA, 1989.
16. Hofmann-Wellenhof, B.; Lichtenegger, H.; Wasle, E. *GNSS—Global Navigation Satellite Systems*; Springer: Vienna, Austria, 2008.
17. Gili, J.A.; Corominas, J.; Rius, J. Using Global Positioning System Techniques in Landslide Monitoring. *Eng. Geol.* **2000**, *55*, 167–192. [CrossRef]
18. Teunissen, P.J.G.; Montenbruck, O. *Springer Handbook of Global Navigation Satellite Systems*; Springer: Cham, Switzerland, 2017.
19. Li, J.; Heap, A.D. A review of comparative studies of spatial interpolation methods in environmental sciences: Performance and impact factors. *Environ. Model. Softw.* **2011**, *26*, 299–309. [CrossRef]

20. Kebede, H.; Demissie, Z.; Tadesse, H.; Abebe, A.E. Spatial Interpolation Techniques Comparison and Evaluation: The Case of Ground-Based Gravity and Elevation Datasets of the Central Main Ethiopian Rift. *Heliyon* **2024**, *10*, e32806. [CrossRef] [PubMed]
21. Childs, C. Interpolating Surfaces in ArcGIS Spatial Analyst. *ArcUser Mag.* **2004**, *3235*, 32–35.
22. Watson, D.F.; Philip, G.M. A refinement of inverse distance weighted interpolation. *Geoprocessing* **1985**, *2*, 315–327.
23. Blachowski, J.; Ellefmo, S.L. Mining Ground Deformation Estimation Based on Pre-Processed InSAR Open Data—A Norwegian Case Study. *Minerals* **2023**, *13*, 328. [CrossRef]
24. Hu, L.; Zhang, Y.; Chen, W.; Liu, Y.; Li, X. Monitoring Surface Deformation Dynamics in the Mining Subsidence Area Using LT-1 InSAR Interferometry: A Case Study of Datong, China. *Int. J. Appl. Earth Obs. Geoinf.* **2024**, *132*, 104099. [CrossRef]
25. Lian, X.; Shi, L.; Kong, W.; Han, Y.; Fan, H. Residual Subsidence Time Series Model in Mountain Area Caused by Underground Mining Based on GNSS Online Monitoring. *Int. J. Coal Sci. Technol.* **2024**, *11*, 27. [CrossRef]
26. Marschalko, M.; Yilmaz, I.; Bednárik, M.; Kubečka, K. Deformation of Slopes as a Cause of Underground Mining Activities: Three Case Studies from the Ostrava–Karviná Coalfield (Czech Republic). *Environ. Earth Sci.* **2012**, *66*, 1201–1214.
27. Singh, R.P.; Dhar, B.B. Influence of Mine Geometry on Surface Subsidence Prediction. *Int. J. Rock Mech. Min. Sci.* **1997**, *34*, 1147–1158. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.