Monitoring deformation processes of Provadia salt depot area (13951)

Mila ATANASOVA-ZLATAREVA and Keranka VASSILEVA, Bulgaria

Key words: technogenic deformations, InSAR, EGMS, Provadia salt deposit, geodetic geodynamic network

SUMMARY

Our research interest is focused on determining the earth's crust deformations that have occurred in the area of the Provadia salt depot (Bulgaria). An archaeological site of the Solnitsa-Provadia is located in the areas, as well. The research is many years old and it is now being supplemented with data provided by the European Ground Motion Service EGMS for a 5-year period. Since the mid-20th century, Provadia salt deposit underwent intensive industrial salt extraction. The area is exposed to various anthropogenic, tectonic, seismic acting mixed with different intensity. In the area seismicity is characterized with frequent low-magnitude earthquakes no greater than M<2.5 over the last few decades. The EGMS data has been used to monitor contemporary geodynamic processes in the salt deposit region Provadia. The InSAR method was applied to study surface deformations for the period 2019-2024. The displacements are compared with the multi-year repeated results from geodetic measurements of the Provadia geodynamic network. The results of this study show that the activity on the Earth's crust in the area still goes on and confirm that the methods applied are appropriate for determining the technogenic movements of the earth crust.

РЕЗЮМЕ (български)

Нашият изследователски интерес е фокусиран върху определянето на деформациите на земната кора, възникнали в района на солното депо Провадия. В района се намира и археологически обект Солницата. От средата на 20-ти век, солното находище Провадия е подложено на интензивен промишлен добив на сол. Районът е изложен на различни антропогенни, тектонични и сеизмични въздействия, смесени с различна интензивност. Сеизмичността в района се характеризира с чести земетресения с нисък магнитуд (M<2.5) през последните няколко десетилетия. Изследването е многогодишно и сега се допълва с данни, предоставени от Европейската служба за движение на земята (EGMS) за 5-годишен период. Данните от EGMS са използвани за наблюдение на съвременните геодинамични процеси в района. Методът InSAR е приложен за изследване на повърхностните деформации за периода 2019-2024 г. Премествaнията са сравнени с резултати от многогодишните геодезически измервания на геодинамичната мрежа. Резултатите от това проучване потвърждават активността на земната кора в района.

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1. INTRODUCTION

Mirovo salt deposit near the Provadia town, Bulgaria is a unique natural phenomenon for the country, both in its origin, form, composition and location and in geophysical characteristics. In the area there are many faults with different spatial orientation, forming a complex tectonic unit, which forms the very diapir pressing of the salt (Fig.1). The prehistoric complex of Provadia-Solnitsa is located near the Provadia town in Northeastern Bulgaria. It represents the remains of the oldest salt-extracting center in Europe (5600 - 4350 BC), which became the first prehistoric urban center on the European continent (4700 - 4350 BC) (https://provadia-solnitsata.com/bg/). Archaeological research of the prehistoric salt-extracting and urban center of Provadia-Solnitsa began in 2005 and has been ongoing for 20 archaeological seasons (Nikolov, V., 2016).

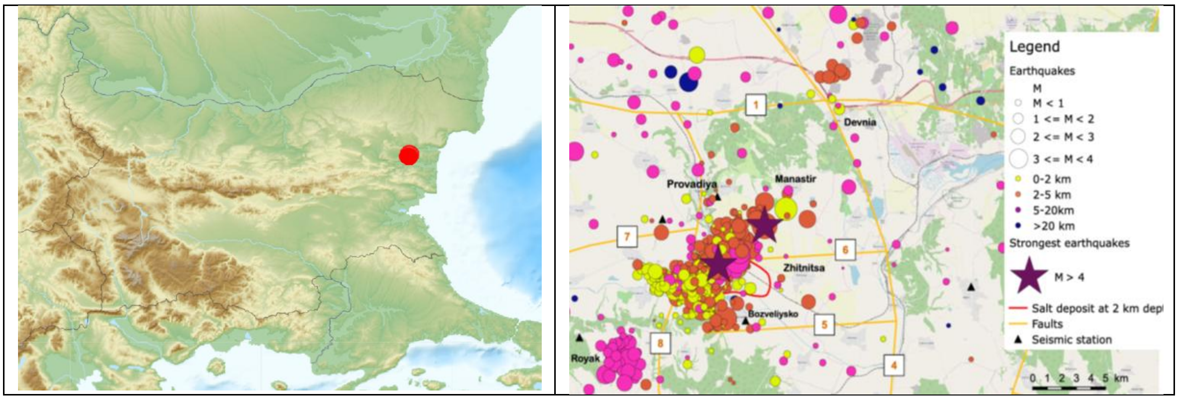

Figure 1. Location of Provadasol; Spatial distribution of the earthquakes' epicenters in the Provadia region for the period of 2006 to 2018 (Dimitrova et al., 2020).

The Mirovo salt diapir has a depth of approximately 4000 m and its top (the "salt mirror") is 15 to 20 m deep. The diapir has a base area of the order of 200 km2 and generally has the shape of a truncated cone. The industrial exploitation of the salt pit began in 1954 after the construction of the first soda plant in the Devnya lowland. The method of boring is applied at present in the salt pits (more than 30 utilized boreholes) and more specifically the method of underground salt leaching through which one major raw material for the Devnya chemical plants is produced -brine (Valev et. al., 1999).

It is known that the rapid movement of the earth crust appears as one of the most important short-term precursors of earthquakes. Therefore it was necessary to be carried out periodic geodetic measurements in order to obtain reliable information about the horizontal and vertical movements and deformation processes of the earth crust, resulting in compression, extension, sinking, tilting. The aim of this work is to examine how far exploitation of rock-salt is connected to local seismic activity because recently earthquakes occur here more frequently.

2. SEISMOLOGICAL AND TECTONIC SETTINGS OF THE AREA

The Provadia region is characterized by weak seismic activity that began in the 1970 (Paskaleva et. al., 2010; Botev, E et. al., 2006). Over the past 50 years, approximately 15 earthquakes with magnitudes greater than 3.5 and more than 350 events with magnitudes exceeding 1.5 have been recorded. These are shallow earthquakes, occurring at depths of up to 10 km. On average, several earthquakes with magnitudes above 3.5 occur per decade. This concentration of seismic events is related to the intersection of several fault structures (Fig. 2). In the area surrounding the salt body, tectonic stresses arise from ground surface movements, and the accumulated energy is released in the form of weak earthquakes. Seismic monitoring in the region is carried out by a local seismological network consisting of four permanent and two temporary stations, all equipped with modern broadband digital sensors and data acquisition systems (Dimitrova et al., 2010).Tectonically, the studied region includes parts of the Moesian platform, Provadia syncline, Lower Kamchia basin and Fore-Balkan (Fig. 1). The territory is characterized by complex geological and tectonic structures. Although the area is considered seismically weakly active, a significant number of earthquakes occur in the region. (Dimitrova et al., 2020).Weak seismicity is observed along well-defined and well-known fault structures in the region. The most seismically active area is located between the South Moesian subequatorial fault and the North Sub-Balkan fault. Most of the earthquakes are concentrated in the central part of the Provadia Valley, which is underlain by the Mirovo salt deposit. A significantly higher number of earthquakes occurs within the salt body area and up to 1 km southwest of it. Earthquake magnitudes reach up to 3.1, while focal depths reach approximately 5 km (Fig. 1) (Dimitrova et al., 2010).

3. METODS and DATA

3.1. Geodetic methods

Geodetic methods as the most accurate methods for extracting natural geometric quantities have been applied for monitoring of surface movements of the area of interest. Local geodynamic networks of 26 pillars have been established especially to monitor surface movements and deformations in the deposit area using precise angular and distance measurements and GPS (Fig. 2). GPS has been used to determine the control sites, once per year but recently it is regularly implemented for precise positioning of all the network sites (Milev et. al., 1994). The main tasks in deformation analysis are to describe crustal movements and the movements or the displacements of objects, such as landslides, buildings.

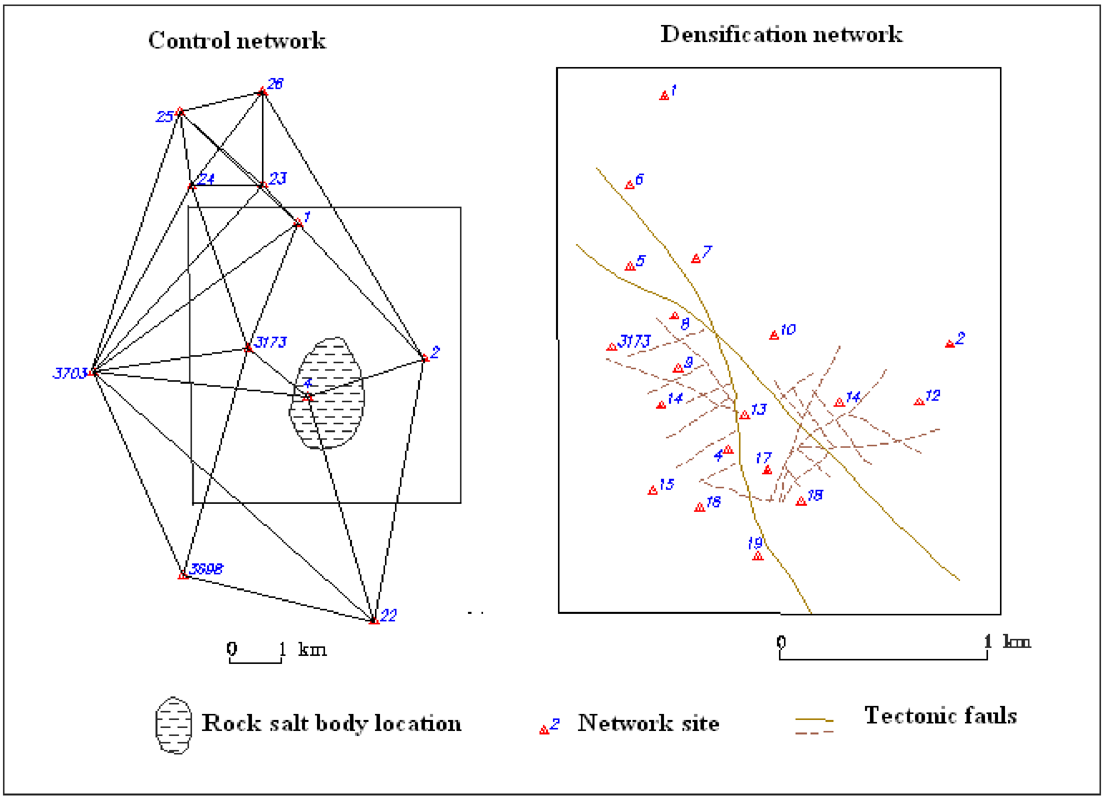

Figure 2. Provadia geodynamic network and faults (Milev et. al., 1994)

Besides precise GPS observations, measurements of the horizontal directions, EDM distances, heights and astronomical azimuths were carried out. For evaluation of the natural and technogenic risks in the Mirovo salt deposit the data from detail geodetic monitoring of network of periodical (each year) precise measurements in the zone of Mirovo salt deposit have been analyzed. Based on the results of periodic leveling measurements, the annual subsidence and the corresponding annual vertical velocities of all benchmarks have been calculated (Fig. 3).

Between 1990 and 2016, the largest benchmark sinking of 875mm was found in the central part of the deposit. (Valev et. al., 2015). The subsidence of the other benchmarks varies between 250 mm and 500 mm. The sinking is attenuating towards the peripheral part. There is no uplifting anywhere. During this relatively long period none of the benchmarks has kept its position. There is sufficient reason to believe that the behavior of these benchmarks is a reflection of deformations that occurred in the salt body. The subsidence of the boreholes corresponds very well with the rheology of the salt-rock mass, both in size and in distribution.

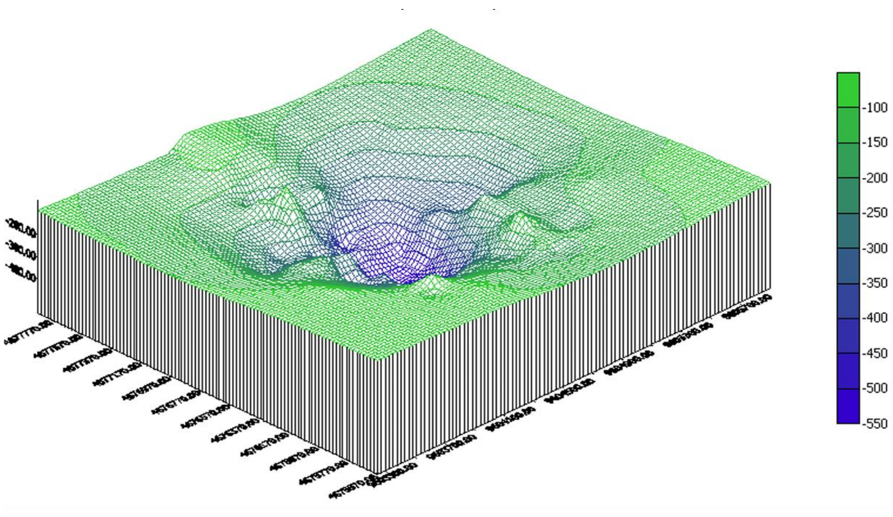

Figure 3. 3D image of the subsidence of the earth's surface (Valev et. al., 2015)

Mathematical model for combined three-dimensional adjustment of classical and GPS measurements for the adjustment are used for several epochs of measurements, including: horizontal directions, distances, height differences and GPS observations.

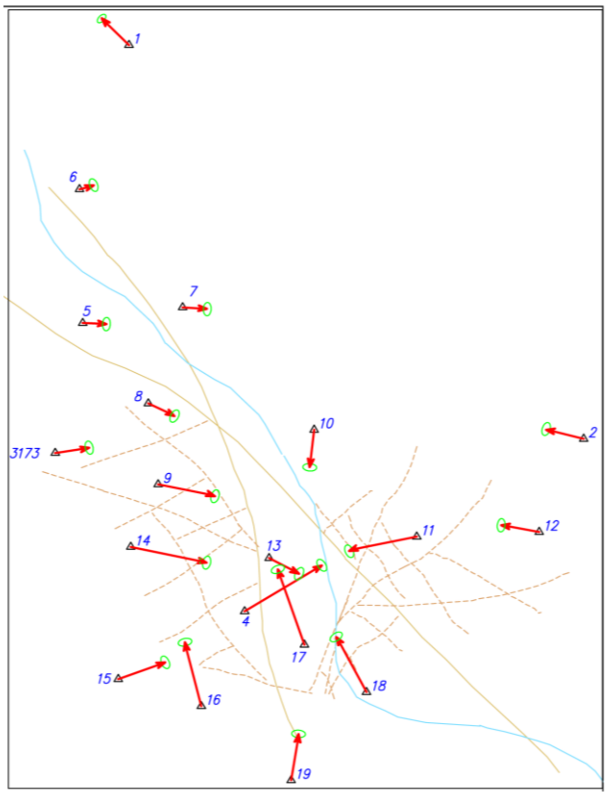

Figure 4. Relative velocities in the region of Provadia salt depot (Atanasova, 2015)

The obtained horizontal velocities give an idea of the nature and direction of motion of the points. The values and directions of horizontal velocity vectors shown in Figure 4 clearly shows that the deformation process continues with a slightly variable rate but with the same trend and confirm (Valev et. al., 2000) tendency to move the points to the center of the salt body. The obtained horizontal velocities of the points within the salt body are about 20mm/yr. Stations 4,11,14,16,17 and 18 show maximum velocities of 12.6-18.5 mm/yr and maximum significant subsidence for point 13 with velocities of – 24.3 mm/yr (Fig. 4) (Atanasova, 2015). The zones of compression and extension have been defined by applying the Finite Elements Method. Under the assumption that the deformations occurred between observations epochs are isotropic within the boundary of a single differential triangle (finite element), the finite element method has been applied to be analyzed deformations. Relative principal deformations and the direction of the principal deformation have been calculated for each finite element. Analyses of the obtained deformations show that there are deformations of both extensions (dilations) and compressions. In the central part of the deposit there are obtained mainly deformations of compression and their values are the largest. In the peripheral parts deformations are of both types and they are smaller (Atanasova 2015; Valev et. al., 2017).

Geodetic network located in the area of the salt body, constantly alters its configuration and position of the points, as the area is exposed to various anthropogenic, tectonic, seismic attracting acting mixed with different intensity.

3.2. InSAR

Ground-based monitoring is often impractical due to high costs, time constraints, and safety risks, while structural failures can lead to severe human and economic losses. Satellite-based differential radar interferometry offers a reliable and cost-effective remote sensing alternative. In particular, Multi-Temporal InSAR (MT-InSAR) techniques, especially Persistent Scatterer (PS)-based approaches, enable effective monitoring of infrastructure and geological processes without field surveys, relying on SAR image archives.

InSAR measures surface displacements by analysing phase differences between SAR images acquired at different times. Differential InSAR (DInSAR) has been widely used to detect ground deformation related to mining, hydrocarbon exploitation, gas storage, and groundwater extraction. However, conventional DInSAR is limited by atmospheric artefacts and temporal and geometric decorrelation. MT-InSAR overcomes these limitations by exploiting large stacks of SAR images from the same sensor, reducing non-deformation-related phase contributions and enabling displacement time-series analysis (Crosetto et al., 2021).

MT-InSAR techniques identify stable reflectors, known as persistent scatterers, typically associated with man-made structures or stable natural targets, allowing millimetre-scale deformation measurements. Persistent Scatterer Interferometry (PSI) mitigates atmospheric effects by modelling time-dependent deformation for each scatterer, while SBAS reduces decorrelation through short temporal baselines. Deformation is measured along the satellite line of sight relative to a reference point, enabling the reconstruction of accurate deformation time series (Becattini et al., 2025).

3.3. EGMS

The European Ground Motion Service (EGMS), part of the Copernicus Land Monitoring Service (CLMS), provides free pan-European ground motion data to support local and regional ground deformation analyses (Crosetto, Solari, 2023; Crosetto et al. 2025). EGMS provides three product levels: Basic (L2a), offering line-of-sight displacement measurements for ascending and descending geometries; Calibrated (L2b), aligned to a common geodetic reference frame using GNSS velocity models; and Ortho (L3), delivering vertical and east–west displacement components derived from combined L2b datasets. In this study, L2b ascending and descending products and the L3 vertical and horizontal components, resampled to a 100 m grid, have been used (https://egms.land.copernicus.eu/). Since 2016, Sentinel-1 has provided consistent, freely accessible observations, making it well suited for long-term time-series ground deformation analysis.

Radar interferometry based Sentinel-1data has revealed surface deformation associated with salt-extraction-induced subsidence in Solotvyno, Ukraine (Szűcs et. al., 2021; Dobos et. al., 2022)., Vauvert, France (Furst et. al., 2021) and Hunan Province, China (Xing et. al., 2022); surface uplift in previously unrecognized active salt diapirs has been observed in the East Carpathians Bend, Romania (Manea et. al., 2021); and active salt diapirs in Iran have been studied using InSAR integrated with remote-sensing structural mapping (Mohammadnia et. al., 2021; Gang Li et. al., 2024). In Tuscany, Italy, InSAR detected abrupt deformation increases associated with overexploitation in industrial areas (Medici et. al., 2024), while open-access datasets from the European Ground Motion Service have enabled monitoring of underground gas storage facilities in Germany and Spain (Fibbi et. al., 2023, 2025). ENVISAT SAR data in Iran have provided insights into the behavior of over 200 subaerial salt extrusions in the Zagros Mountains and surrounding deserts (Baikpour, et. al., 2010), and L-band SAR from ALOS-1 has been used to identify landslides associated with salt mining in western New York, USA (Val et. al., 2016).

In the Provadia area, InSAR-based detection of crustal deformation was first implemented in 2016 (Atanasova-Zlatareva & Nikolov, 2016). Subsequent studies applied InSAR to analyze ground deformation at the Solnitsata–Provadia archaeological site (Nikolov & Atanasova, 2021, 2022) and to detect surface displacements along a railway line near the Mirovo salt deposit (Atanasova-Zlatareva & Nikolov, 2022). PSInSAR results indicate an average line-of-sight subsidence rate of −22.6 mm/yr for the 2015–2020 period (Ponco et al., 2022). EGMS data have been used investigate the deformation dynamics of the Solnitsata–Provadia cultural monument (Becattini et al., 2025).

4. RESULTS

In this study, MT-InSAR data have been obtained from the European Ground Motion Service, which provides wide-area ground motion monitoring based on Sentinel-1 mission data

(Costantini et al. 2021). The main focus of this study is the application of free, open-access data from the EGMS, which provides user-friendly, large-scale products, significantly enhancing the accessibility of InSAR for monitoring both natural and anthropogenic processes and an analysis of surface displacement without substantial financial or time investments.

Displacements along the Line of Sight (LOS), as well as vertical and west-east (W-E) horizontal components have been determined in this study. As it is known for SAR sensors, the measurement of deformation has low sensitivity in the N-S direction and its determination is limited. The interferometric images obtained with ascending and descending acquisition geometry are sufficient to calculate vertical and horizontal (E-W) displacement components. The EGMS data used are derived from Sentinel-1A interferometric radar images, covering the period from January 2019 to 2024.

To determine vertical displacements, data from both ascending and descending orbits are required. For each pixel, the average displacement velocity along the LOS, the root mean square error (RMSE) of this velocity, and coherence values has been calculated. Figure 5 shows the ground deformation in the LOS direction derived from ascending and descending orbits over the five-year study period. These data have been subsequently used to compute vertical and W-E horizontal displacements.

Surface movement between two SAR acquisitions produces a phase shift, which is spatially represented in the interferogram. The phase shift quantifies how much the Earth's surface moves toward or away from the sensor, which is not located at the local geographic zenith. Pixels moving toward the sensor are displayed in cool blue tones, while pixels moving away are shown in warm colors ranging from yellow to red. The LOS displacement depends on the orbit geometry, which varies between ascending and descending passes.

Displacements are determined only for targets that maintain high coherence across the SAR image stack (coh > 0.65). Such targets typically include stable natural reflectors (e.g., rocks) or artificial structures (e.g., buildings), which preserve consistent dielectric properties over the observation period. This criterion is particularly suitable for the Provadia salt mining complex, which features minimal vegetation and numerous artificial structures acting as permanent reflectors (Fig. 1).

The EGMS Ortho product allows a combination of data from more than two orbits, when available, enabling more comprehensive displacement analysis for the study area.

Figure 5 presents the surface displacements recorded along the satellite line of sight (LOS) for the Provadia salt mining complex (Fig. 1), derived from calibrated EGMS data for the period January 2019 – December 2023. The analysis is based on Sentinel-1 acquisitions from ascending orbits 58 and 131 and descending orbits 36 and 109. Figures 5a and 5b show the mean LOS velocity maps and the corresponding displacement time series for the ascending and descending geometries, respectively.

A clear subsidence signal is observed in the central part of the salt deposit. This deformation pattern is consistently captured by the multi-temporal InSAR technique, revealing pronounced subsidence in the central zone with mean LOS velocity values reaching up to −28 mm/yr. The spatial extent and magnitude of the subsidence distinctly contrast with the surrounding relatively stable areas.

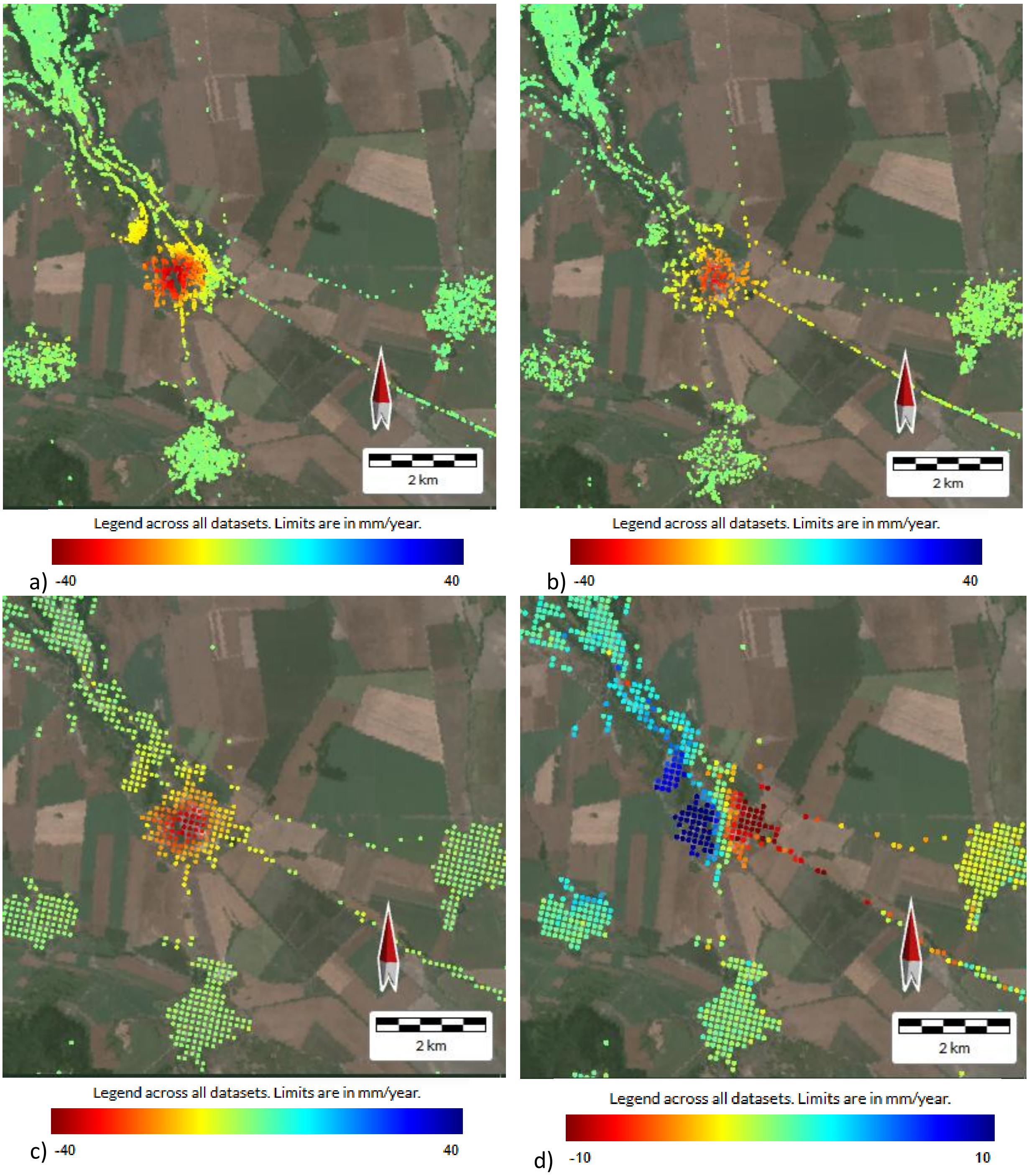

Figure 5. Mean LOS velocity (mm/yr) and time series Jan 2019-Dec2023 for the a) ascending 58 and 131 and b) descending orbits orbits 36 and 109 calibrated EGMS;

c) Vertical and d) horizontal east–west displacements derived from MT-InSAR for the period January 2019–December 2023, based on data EGMS Ortho (https://egms.land.copernicus.eu/)

The multi-temporal PS-InSAR approach provides a high density of measurement points characterized by strong temporal coherence. For both ascending and descending tracks, subsidence affecting the central part of the deposit is clearly detected, with maximum LOS velocity values of −36.2 mm/yr for ascending orbits A58 and A131 and −34.1 mm/yr for descending orbits D36 and D109.

Figures 5c an 5d presents an example of the EGMS Ortho products, illustrating the derivation of vertical and horizontal east–west displacement components from line-of-sight (LOS) measurements obtained from MT-InSAR time series acquired along four satellite orbits. The decomposition of LOS displacements from both ascending and descending geometries enables the estimation of the vertical and horizontal (E–W) components of the displacement vector.

EGMS map (Fig. 6) clearly delineates a cluster of pixels located in the central part of the salt body, characterized by a pronounced deviation from stable behavior. This deformation pattern stands out distinctly from the surrounding areas and confirms the presence of significant subsidence in the central zone of the study area. The observed vertical subsidence is accompanied by inward-directed horizontal displacements from the peripheral parts of the deposit toward its center.

Within the subsidence zone, a collision-type deformation pattern is observed, characterized by horizontal displacements in opposite directions (Fig. 5d). Specifically, westward movements dominate in the eastern zone, while eastward movements prevail in the western zone. For these zones, as well as for all points included in the geodynamic network, displacement time series corresponding to selected representative pixels were extracted in order to analyze the temporal evolution or stability of the observed deformation.

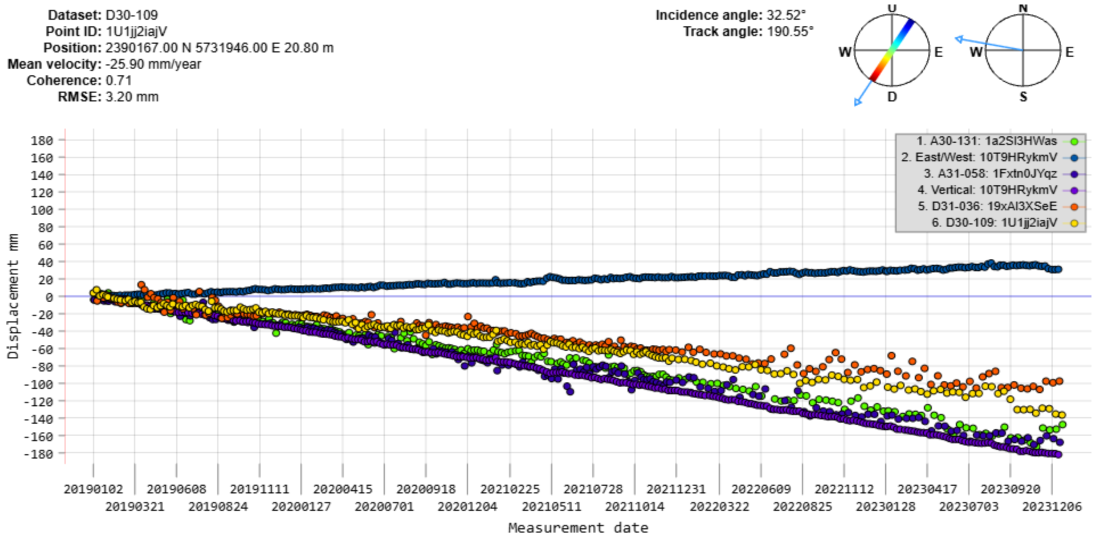

Figure 6. Displacements derived from MT-SAR time series based on descending orbits 36 and 109 and ascending orbits 58 and 131 for the period January 2019–December 2023, using EGMS data (https://egms.land.copernicus.eu/).

Figure 6 represents point located in the central part of the salt body, which is most strongly affected by deformation processes. The point has WGS84 coordinates 43.1322° N, 27.4705° E, and an elevation of 22.77 m. The analysis includes data from ascending orbits 58 and 131 and descending orbits 96 and 109 over the period January 2019–December 2023, derived from calibrated EGMS data. By combining line-of-sight (LOS) displacement measurements from both ascending (green and blue) and descending (red and yellow) orbits, the vertical (dark purple) and horizontal east–west (light blue) components of the displacement vector have been estimated (Fig. 6). The observed surface displacements at this location indicate an average vertical displacement rate of −36.8 mm/yr, with an RMSE of 0.80 mm. The horizontal east–west displacements are several times smaller, showing an average westward velocity of approximately 7 mm/yr with an RMSE of 1.10 mm.
Similar analyses were done for all points of the geodynamic network (Fig. 2). The comparison between displacements derived from the EGMS model and those obtained from the combined adjustment of geodetic measurements demonstrates good agreement between the two datasets.

CONCLUSION

The present study shows that the region is exposed to various impacts (technogenic, tectonic, seismic), which act differently and with varying intensity in space and time, but the predominant influence is that of salt extraction. The deformations are not uniform across the area due to multiple faults, differences in rock breeds, and variation in salt extraction in individual zones and drilling chambers.
This study demonstrates the application of Multi-Temporal InSAR (MT-InSAR) for monitoring subsidence related to technogenic processes. A case study of the Provadia salt deposit illustrates the effectiveness of satellite radar interferometry as a routine, space-based tool for assessing structural stability through the analysis of vertical and horizontal ground displacements.
The European Ground Motion Service data have been used to evaluate the surface ground behaviour in the Provadia area from 2019 to 2023, providing detailed information on ground motion patterns. The results reveal the current subsidence conditions and confirm the reliability of MT-InSAR for long-term monitoring of surface deformation.
Importantly, InSAR demonstrates substantial potential for future applications. Integrating complementary datasets - such as seismic data, GNSS measurements, levelling surveys, borehole monitoring, and reservoir parameters - can enable a more comprehensive, multidisciplinary understanding of subsurface processes. By combining multiple sources of information, InSAR could serve as a cornerstone of early warning systems, capable of detecting changes in deformation trends, mitigating hazards, enhancing operational efficiency, and safeguarding communities. Overall, the findings highlight MT-InSAR as a powerful, cost-effective, and scalable tool for proactive risk management and sustainable resource operations.

ACKNOWLEDGEMENTS

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BIOGRAPHICAL NOTES

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