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Post-mining deformations in the area affected by the former "Siersza" Hard Coal Mine in Trzebinia (southern Poland)

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Over the recent years, post-mining terrain deformations has been increasingly frequent around Trzebinia. Sinkholes appearing increasingly close to buildings have become a significant geohazard. We show that post-mining deformations in the area is much more extensive than previously estimated. Identification of the deformations involved analysis of historical aerial photographs, airborne laser scanning data, orthophotomaps and satellite radar data. Moreover, laser scanning of selected areas using an unmanned aerial vehicle and a terrestrial laser scanner was carried out together with field mapping. In the study area, 527 sinkholes and 254 linear-type deformation structures were identified. Comprehensive mapping of sinkholes – including those previously unknown, located outside built-up areas – showed that areas where sinkholes had been remediated in the past were also at significant risk. A number of sinkholes are also located outside areas of shallow (up to 100 m below ground level) mining. The use of satellite radar interferometry showed that continuous deformations also occurs in the area of influence of the former "Siersza" Hard Coal Mine. In the past, subsidence of this terrain took place, while currently uplift is taking place in this area which locally reaches up to 20 mm per year.

Key words: sinkholes, post-mining deformations, InSAR, DTM, multitemporal lidar, Upper Silesia Coal Basin.

INTRODUCTION

Mining evidence near Siersza (the present Trzebinia settlement) indicates that local coal mining took place here as early as the mid-18th century. The first "Albrecht" mine in the area opened at the beginning of the 19th century (Pietraszek, 1961). Subsequently, interest in exploiting shallow coal seams increased, and several other mines opened that operated until 1852. Coal mining resumed in 1861 at the "Nowa Izabela" mine, which operated, like the "Artur" mine, from 1884. After the Second World War, the "Artur" and "Zbyszek" mines were merged, which gave rise to the "Siersza" Hard Coal Mine. Since 1949, the mine has greatly expanded, progressively increasing its area of exploitation to reach ~40 km^2. The development of mining in the area was due to shallow coal seams exploited at depths of several tens of metres below ground level. The Carboniferous coal-bearing succession typically lies directly beneath Quaternary deposits. The exploitation of hard coal was possible thanks to permanent pumping during the mining.

The "Siersza" Hard Coal Mine ceased operation in 1999, and a year later the pumping of water stopped. The entire process of mine decommissioning ended on 31.12.2002, including backfilling of the shafts. The cessation of pumping resulted in flooding of the mine, which was expected to fill the voids by 2011 (Frolik, 2006). Yet the time span was underestimated, as the groundwater table has still not fully recovered. Twenty-one years after pumping stopped, the problem of post-mining deformation, especially sinkholes, has intensified significantly. An increasing number of sinkholes have started to appear in the vicinity of buildings, causing damage to infrastructure and increasing the risk to residents.

Although the effects of mine decommissioning through flooding have been discussed (e.g., Kleta and Plewa, 2001; Frolik, 2006) the timing and effects of this mine's flooding are only now known in more detail.

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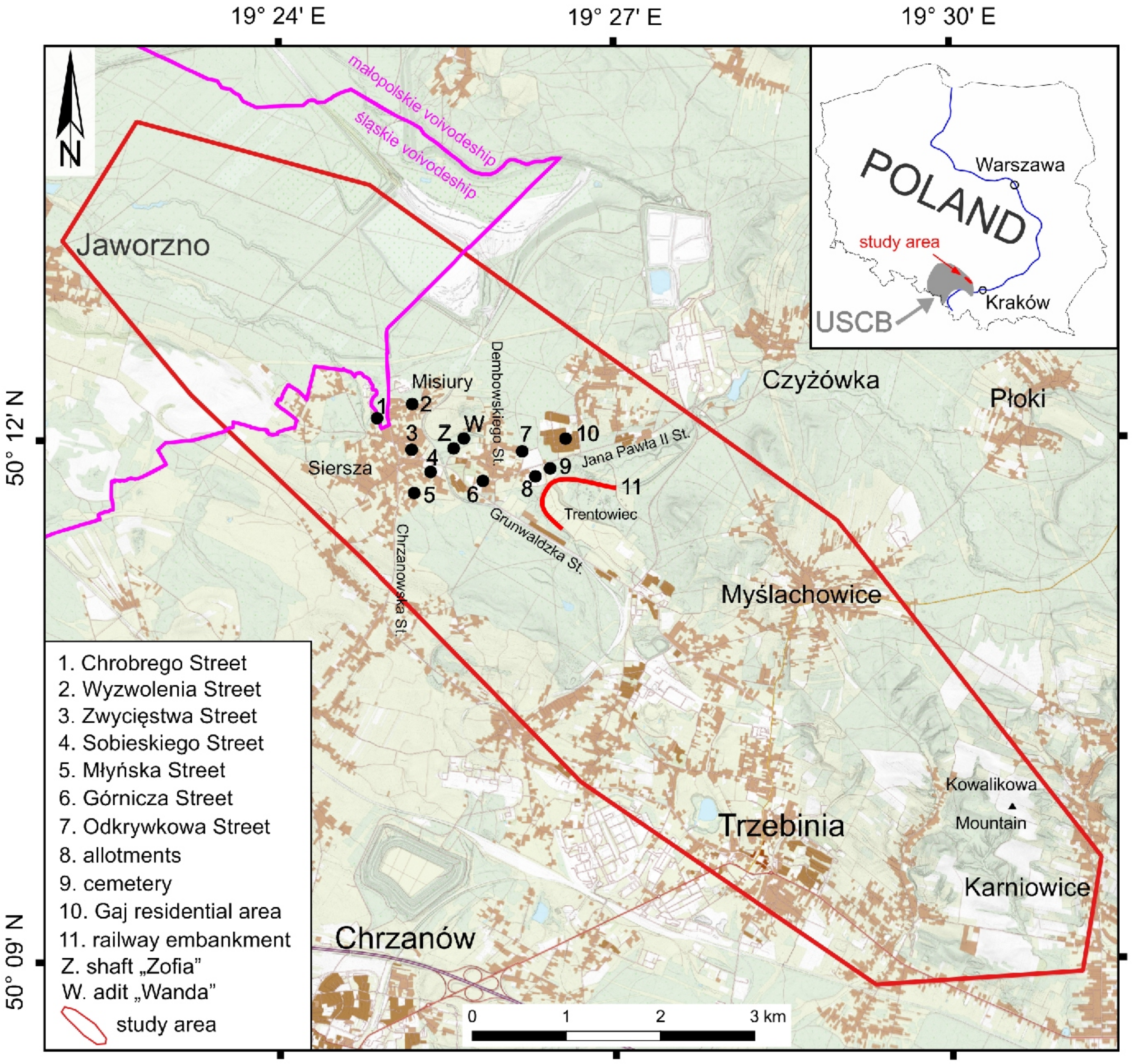

Fig. 1. Study area; USCB – Upper Silesian Coal Basin

This research catalogues, identifies the causes of, and forecasts the possibility of further post-mining deformations in the area affected by the former "Siersza" Hard Coal Mine. The boundaries of the Siersza coal deposit from 1999 were adopted as the limits of the study area. The comprehensive documentation of sinkholes across the whole area allowed the determination of their common features.

STUDY AREA AND GEOLOGICAL SETTING

The Siersza deposit covers an area of 40.3 km^2 and is situated in southern Poland, on the border of the Silesian and Lesser Poland voivodeships, in the north-eastern part of the Upper Silesian Coal Basin (USCB), in the region of the Wilkoszyn Basin (Fig. 1).

Upper Carboniferous coal-bearing formations are of primary importance in the USCB area. Within the boundaries of the Siersza deposit, these are overlain by Permian Triassic, Jurassic, Neogeneand Quaternary formations of varying thickness and distribution (Jureczka et al., 2005; Fig. 2). The top of the Carboniferous is deepest-lying in the southern part of the area where it is buried below Triassic deposits (the Carboniferous top lies at ~+30 m above sea level, the overburden reaching a thickness of >280 m) and in its eastern part beneath Permian deposits where the overburden reaches >170 m thick (Fig. 2).

Quaternary deposits (fine- and medium-grained sands, clays and loams) with a thickness varying from 0.2 to 54.6 m cover the whole area. In the central part of the area, the Quaternary deposits lie directly on top of the Carboniferous with a thickness not exceeding 30 m. Outcrops of coal seams also oc-

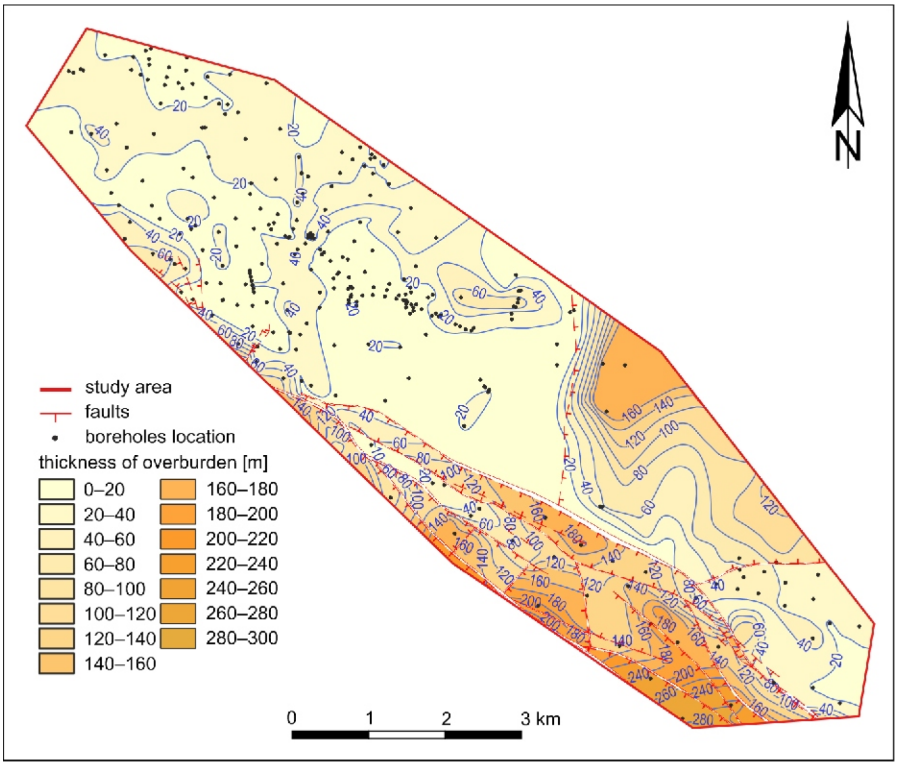

Fig. 2. Thickness map of overburden above the Carboniferous (data from borehole records included in the mine documentation)

cur in this area. Moreover, above the Carboniferous strata there are Permian and Triassic beds located mainly in the southern and eastern part of the area (Fig. 2). The Permian formations, ranging in thickness from ~20.0 to 172.5 m, include the Filipowice tuffs and Myślachowice conglomerates (Miśkowicz, 1999). The latter are rocks composed of lower Carboniferous and Devonian limestone and dolomite boulders, which are easily eroded.

Triassic deposits comprise siltstone and claystone, limestone, dolomite, marls, conglomerates, sands, sandstone, and gravels (Miśkowicz, 1999; Skowroński, 2014), locally reaching a thickness of >150 m.

Coal-bearing Carboniferous formations (down to the documented depth of 1,000 m) are represented by the Kraków sandstone series (Libiąż and Łaziska beds), mudstone series (Orzesze and Załęże beds), the Upper Silesian sandstone series (Ruda beds) and the paralic series (Grodziec, Flora and Sarnów beds) are of minor importance (Miśkowicz, 1999; Skowroński, 2014).

The Krakow sandstone series comprise greywackes and arkose sandstones of various grain sizes with thin layers of mudstone and claystone, as well as numerous coal seams, which are characterised by constant depositional palaeo-depth, thickness, and distribution. The underlying mudstone series is characterised by the predominance of siltstones and claystones over sandstones and the presence of coal seams of variable thickness (Polak, 1992; Miśkowicz, 1999). The Upper Silesian sandstone series is formed by sandstones of various grain size, with subordinate siltstones and claystones and unlisted coal seams. The paralic series comprises silty claystone with thin interbedded coal seams (Jureczka and Kotas, 1995).

The tectonic structure of the area located in the eastern part of Wilkoszyn syncline is complex. The basin axis, in which stratal dips do not exceed 15°, is located at the southern boundary of the deposit. The older faults occur only in Carboniferous strata and strike N–S, while younger faults striking E–W occur in both Carboniferous and younger formations (Permian and Triassic). Carboniferous faults of NNE–SSW orientation also occur in the vicinity of the main shafts (Miśkowicz, 1999). Fault offsets are typically a few to several metres, although there are a few faults with offsets over 100 m: the Siersza I, Siersza II, Balin, Trzebinia, Młoszowa and Karniowice faults (Fig. 3).The greatest offset was found in the South fault (150–160 m) and the Border fault (up to 160 m).

In the southern part of the area, the synclinal arrangement of strata is disturbed by a saddle-like elevation with a WNW–ESE axis, with dips of strata ranging from several to >20° (Miśkowicz, 1999; Skowroński, 2014). The younger Carboniferous deposits lie here closer to horizontal, while the coal seams of the paralic series are more inclined.

The objects of exploitation in the Siersza deposit were primarily the seams of the Łaziska beds: 206, 207/1, 208 and, 209, 210, 210/2, 209–210 and 214. Two seams (301 and 303) of the uppermost part of the Orzesze beds were also exploited. To a depth of ~80–100 m below the ground surface (shallow mining), mainly the seams 206, 207/1 and 208 were exploited, and to a lesser extent seams 209–210, 214 and 301. In total, the shallow mining area to a depth of 100 m covers an area of 2.92 km^2 and is located in the central part of the deposit in the area of the Siersza, Misiury and Trentowiec estates (Fig. 4). In some areas, two or even three shallow seams in vertical succession were exploited (Fig. 4). This is the case south-west of

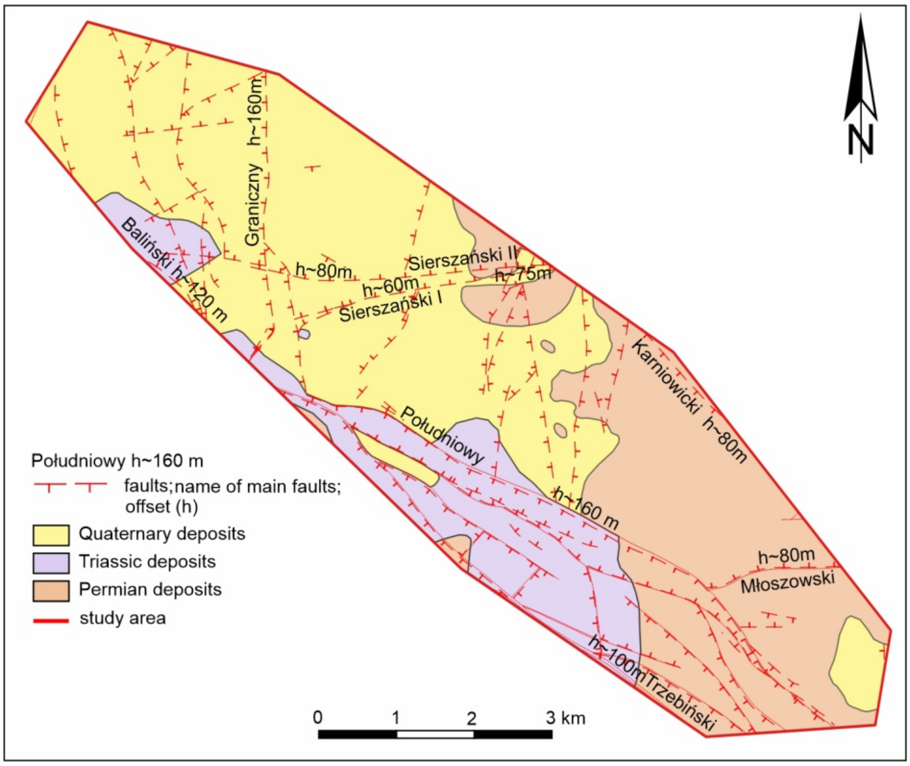

Fig. 3. Carboniferous overburden deposits

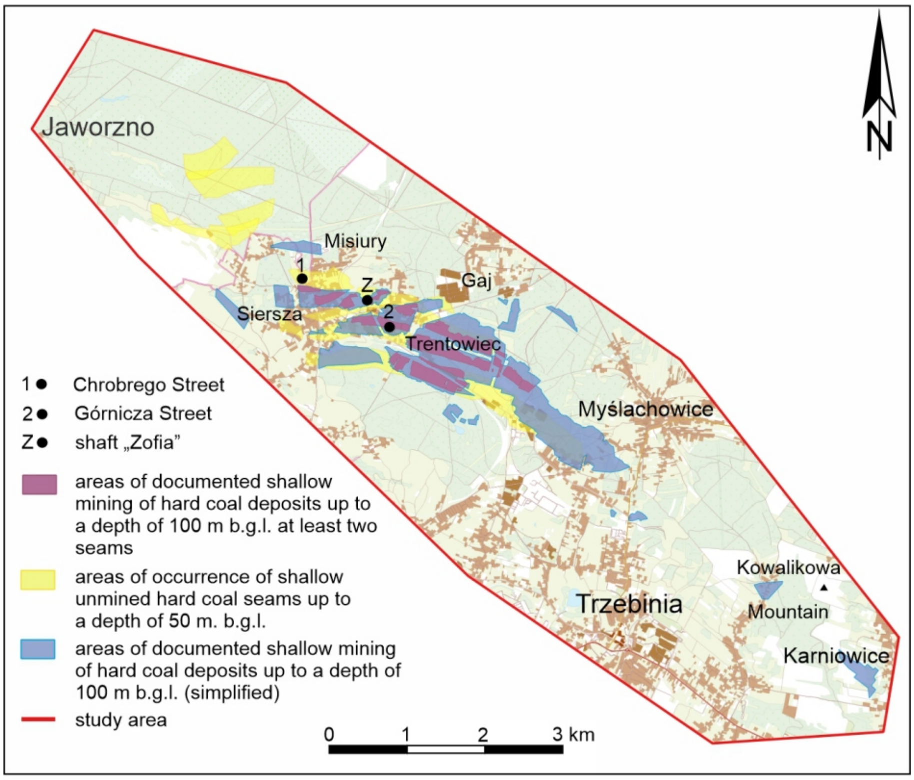

Fig. 4. Map of shallow hard coal deposits

Fig. 5. TLS of a sinkhole near the allotment gardens

the Gaj estate (seams 208, 209 and 210) and in the area of the Trentowiec estate (seams 206 and 207, 207 and 208), Chrobrego Street (seams 208 and 209, 209 and 210), Górnicza Street and the former Zofia casing shaft (seams 207 and 208). In most cases, coal was mined with a roof caving system, and only a few parts of the seams in the northern and western parts of the deposit were mined with hydraulic backfill. In the last decades of the Siersza mine's operation, coal was mined at much greater depths of up 440 m.

Areas where the depth of coal seams does not exceed 50 m below ground level are important, as here there is no information on mining (Fig. 4), because in these areas undocumented exploitation could have been carried out on seam outcrops. These concern mainly the central part of the deposit and eastern areas of Jaworzno.

DATA AND METHODS

A number of remote sensing methods were used to comprehensively map the deformation of the area affected by the former "Siersza" Hard Coal Mine: Interferometric Synthetic Aperture Radar (InSAR), Unmanned Laser Scanning (ULS) and photogrammetric analysis of historical aerial photographs. Multitemporal Airborne Laser Scanning (ALS) data obtained from the Head Office of Geodesy and Cartography (GUGiK), archival orthophotomaps and historical aerial photographs from 1957 and 1987 obtained from GUGiK were also analysed. Selected sinkholes that appeared in the study area during the research were mapped by Terrestrial Laser Scanning (TLS; Fig. 5). The analytical results were verified by fieldwork. Furthermore, processing of satellite SAR data using Persistent Scatterer Interferometry (PSI) was performed for the periods 1992–2002; 2002–2010, 2016–2021 and 2021–2022 in order to analyse continuous ground deformation occurring in the study area. A summary of the remote sensing data used is provided in Table 1.

To determine the causes of sinkhole development and to help predictions, the mapping results were correlated with geological and mining data. The data was sourced from available documentation (including Solski, 1960; Ochoński et al., 1962; Pietrzyk, 1964; Kozłowska and Znański, 1966; Cibis and Solska, 1973; Polak, 1982; Kurek, 1985, 1988; Miśkowicz, 1999; Kozłowska, 2003; Kowalik, 2011; Skowroński, 2014). Archival materials from the resources of the National Geological Archives PGI-NRI (NGA) and the archives of the Supreme Mining Authority were used. Detailed analyses were carried out of 292 borehole sheets, used to determine the Carboniferous overburden thickness and the depths of the coal-bearing beds. Geological maps at 1:5,000 scale and a mining map at 1:1,000 scale were used to locate shallow mines.

InSAR

The analyses carried out using satellite radar interferometry techniques focused on continuous deformations in the area of influence of the former "Siersza" Hard Coal Mine.

SAR interferometry (InSAR) is a technique used to obtain information on relative height data (Goldstein et al., 1988). It utilises phase differences in radar signals from two SAR microwave observations of the same area. The fundamentals of InSAR methodology can be found in publications such as Bamler and Hartl (1998), Massonnet and Feigl (1998), Perski (1999) and Bürgmann et al. (2000). The conventional SAR data processing technique DInSAR (Differential InSAR) involves calculating the phase differences between two SAR images.

Table 1

Summary of applied data

Data type	Source	Timeliness	Application
DTED 2	GUGiK	1980/90	comparison with ALS data – identification of continuous deformations
ALS	GUGiK	2011, 2014, 2019, 2022	DTM, DDTM, identification of discontinuous deformations
ULS	PGI-NRI (made for research purposes)	2023	
Orthophotomaps UAV	PGI-NRI (made for research purposes)	2023	identification of sinkholes
Archival orthophotomaps	GUGiK	1996, 2003, 2009, 2012, 2015, 2017, 2018, 2019, 2021, 2022	
Archival aerial photos	GUGiK	1957, 1987	
TLS	PGI-NRI (made for research purposes)	2023	detailed parametrization of selected sinkholes
InSAR	ESA User Service Portal NASA Earth Observation Data Copernicus EGMS	1992-2002, 2002–2010, 2016–2021, 2021–2022	analysis of continuous terrain deformations
Archival borehole sheets	NGA	1922–1998	determine the thickness of the overburden and the depths of the Carboniferous coal-bearing beds
Archival mining maps and documentations	Supreme Mining Authority	19^{th}, 20^{th} century	location of shallow mines

The result of such processing is a phase difference image called an interferogram, in which the interferometric bands correspond to the deformations of the land surface that occurred between the two SAR image recordings.

PSI processing, on the other hand, is an extension of conventional methods, in reconstructing the deformation history of an area based on the analysis of a time series of interferograms (Ferretti et al., 1999; Crosetto et al., 2015). With this approach, it is possible to decompose the interferometric phase into components and determine deformation increments with very high accuracy (down to 1 mm/year). The displacement information is acquired for image pixels characterised by strong and time-stable radar signal reflections, so-called Persistent Scatterers (PS). These are physical objects whose reflection dominates for a given pixel. They can be roofs and corners of buildings, parts of various types of structures (bridges, fences, etc.), tall telegraph poles or lamp-posts, and specially constructed reflectors (Perissin et al., 2006). In areas without such infrastructure, persistent scatterers are, for example, rock outcrops.

The result of PSI processing is a vector set of PS points, which are assigned values of the movement mean velocity in the Line-of-sight (LOS) direction calculated relative to a reference point and a time series with relative displacement values calculated for each date of the acquired image from the recording period. The PSI method is best suited for monitoring slow continuous changes whose displacement growth trend line will be nearly linear.

Free data from the European Space Agency were used to analyse deformation in the Trzebinia municipality area. In particular, the images used were:

– from the ERS-1/2 SAR IM Single Look Complex Image satellites, downloaded via the ESA User Service Portal Dissemination Service, https://esar-ds.eo.esa.int/, track 451 and 222, for the period 1992–2002;
– from the Envisat ASAR Image Mode Single Look Complex Level 1 satellite, downloaded via the ESA User Service Portal Dissemination Service, https://esar-ds.eo.esa.int/, track 451 and 143, for the period 2002–2010;
– from the Sentinel-1A Level-1 Single Look Complex satellite, downloaded via the NASA Earth Observation Data service, https://search.asf.alaska.edu/, track 124 I 102, for the period 2021–2022;
– Sentinel-1A/B data processing results made available through the Copernicus European Ground Motion Service (EGMS), EGMS (copernicus.eu) for the period 2016–2021.

LASER SCANNING

Laser scanning data exists as a large set of points representing the reflections of a laser beam from different surfaces. Each point has specific horizontal and vertical coordinates. Only points classified as "ground", representing the terrain surface, were used in the analyses. Digital terrain models (DTMs) were then generated at 0.5 m resolution using TIN interpolation. The DTMs generated with ALS and ULS data were used to indicate locations where discontinuous deformation – sinkholes, faults, scarps and, trench fissures – may be present. Meanwhile, TLS data was used to determine the parameters of newly formed sinkholes. A *Riegl VZ-2000i* laser scanner was used for that purpose.

The following criteria were adopted for the diagnosis of sinkholes on DTMs:

– oval or slightly elongated shape in vertical projection;
– at least 0.5 m deep;
– having no bulge around the hole (which may be related to excavation, for example);
– occurring on at least two multi-temporal DTMs or on a DTM and an orthophotomap, or occurring on only one DTM but having a very distinct shape (to eliminate DTM filtering errors).

To determine changes in sinkhole development since 2011 (the oldest available ALS data for the area), digital differential terrain models (DDTMs) with a resolution of 0.5 m were made for the study area. These illustrate the elevation changes between two DTMs made for the same area, from data acquired at

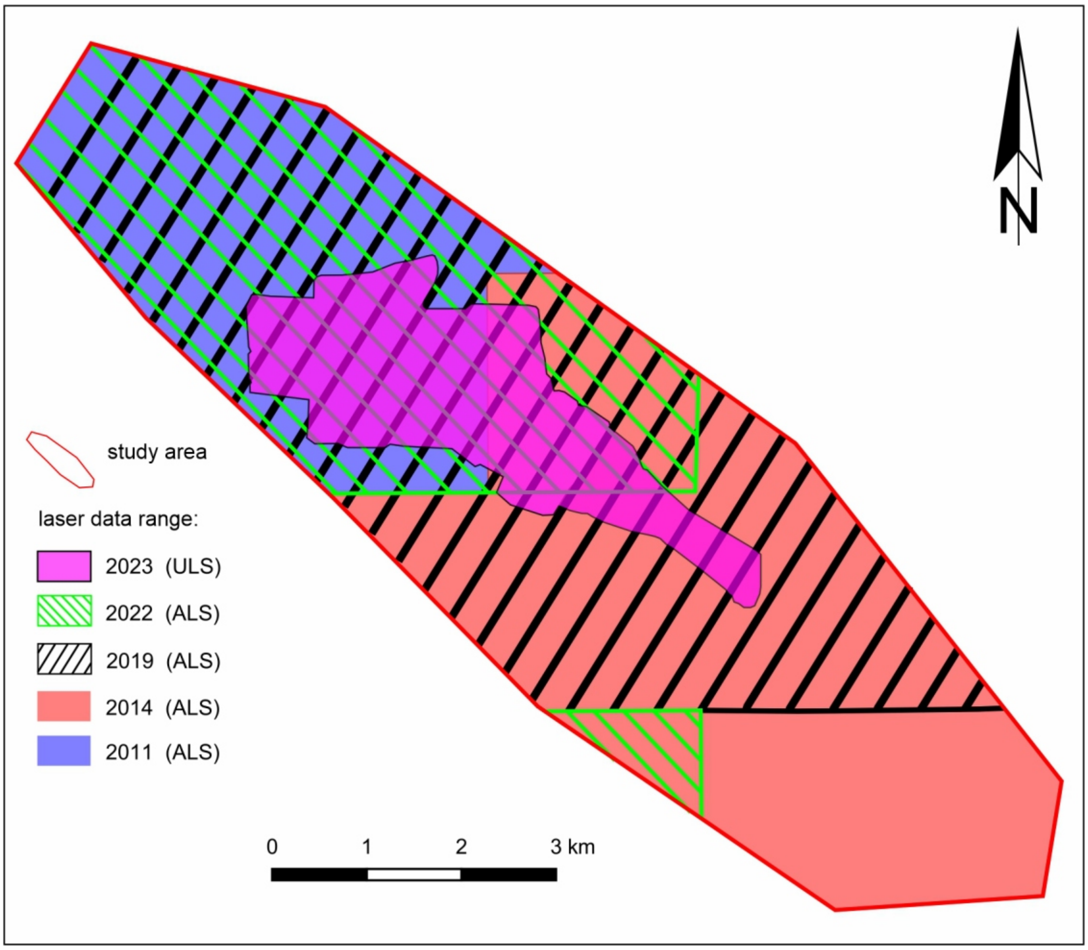

Fig. 6. Extent of laser scanning data

different times. The time of data acquisition, as well as the area for which the scanning was performed, allowed DDTMs to be developed for the following periods: 2011–2019, 2014–2019, 2019–2022 and 2022–2023 (Fig. 6).

To complement the continuous deformation studies, a DDTM was also made based on the 2011/2014 ALS data and a military DTED 2 model with a field validity of the late 1980s and early 1990s and a vertical accuracy of 2–7 m. Despite significant differences in the accuracy of the compared input DTMs, subsidence basins resulting from long-term coal mining were clearly visible in the DDTM image, although the specific values of the differential model obtained are not reliable due to low accuracy.

PHOTOGRAMMETRY

Orthophotomaps and DTMs acquired in photogrammetric flights were used for preliminary identification of sinkholes formed after ALS measurements taken in 2022. A shallow mining area with a total area of 3.64 km^2 was measured using a *DJI Phantom 4 RTK UAV*. High-resolution orthophotomaps (0.04 m) made it possible to detect unknown as well as reclaimed sinkholes.

To document historical sinkholes, archival aerial photographs from manned flights of 1957 were used. A set of 27 photographs, at 1:8,000 scale, was aerotriangulated on the basis of 34 ground reference points, whose position had remained unchanged since the photographs were taken. The accuracy of fitting into the terrain layout at the 4 control points was RMSxy = 2.75 and RMS$_h$ = 0.99 m, which allowed for the use of historical data in comparative analyses with the current data.

RESULTS

The multimethod approach and fieldwork allowed for the comprehensive study of deformations in the area affected by the former "Siersza" Hard Coal Mine. Also, changes in directions of continuous deformations after mine drainage ended, and sinkhole development dynamics over the last 12 years, were possible to determine. The areas with the highest hazard potential of sinkhole occurrence in the future were indicated, due to the similarity of geoenvironmental factors in the places where they most often occurred in the past.

SINKHOLES

As a result of ALS-, ULS-derived DTM analyses and fieldwork, 527 sinkholes were identified (Fig. 7). In the central part of the research area (south of Jana Pawła II Street, allotments, cemetery with nearby forest) the highest density of sinkholes occurs (up to 42 pc/ha, average 12 pc/ha). Many sinkholes have formed within this area in recent years. This has had effects including building and infrastructure damage in the allotments, the collapse of forty graves in the cemetery, and destruction of the railway embankment to the Siersza Power Station (Fig. 8).

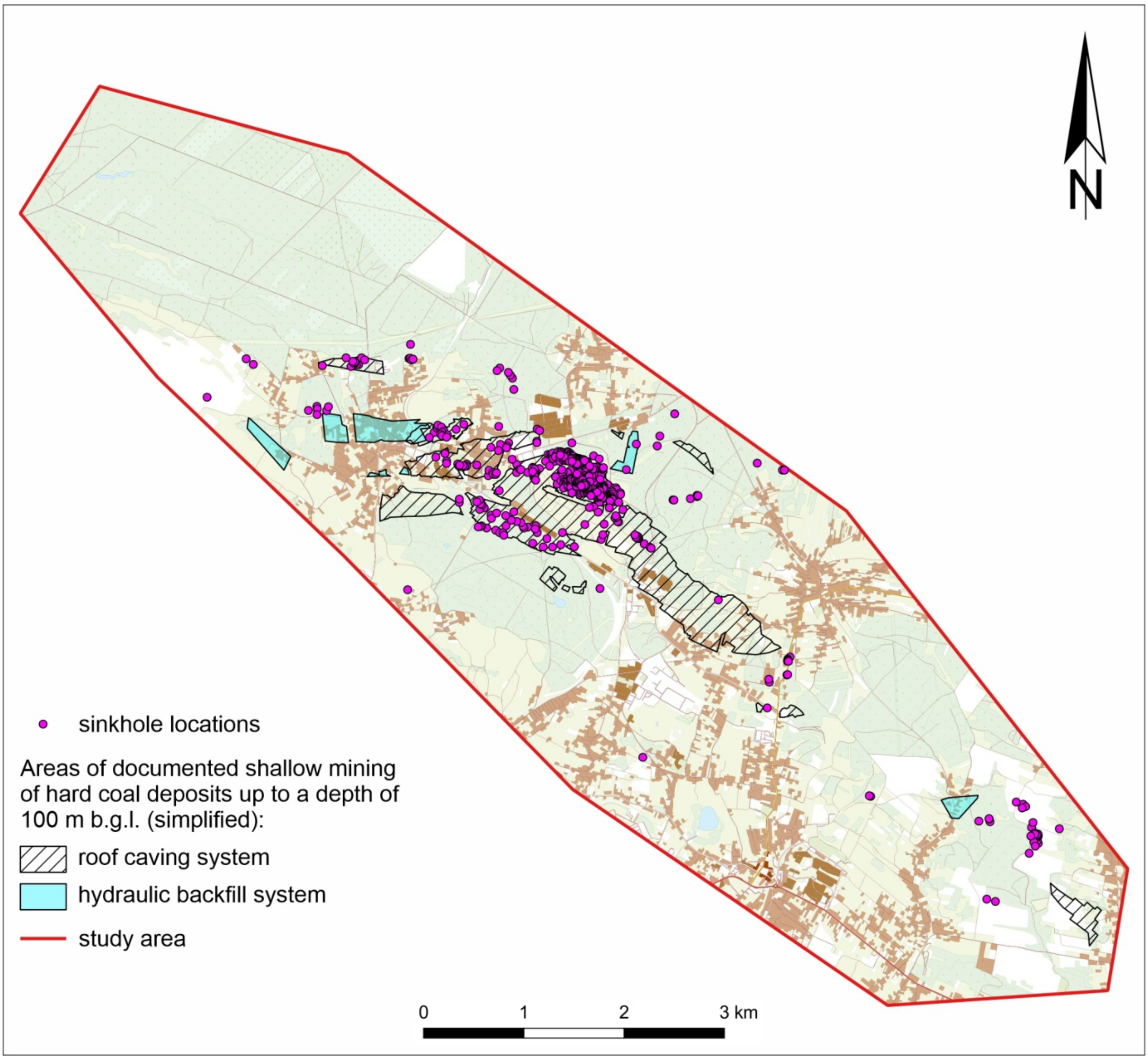

Fig. 7. Location of sinkholes within the study area

The majority of documented forms are characterised by a round or oval shape in plane view and a funnel-shaped cross-section. Those with maximum diameter 5 m predominate. In several cases, the diameter exceeds 20 m. The number of sinkholes decreases as the maximum diameter increases (Fig. 9A). Their depth usually does not exceed 3 m (Fig. 9B). The sinkholes with the largest maximum diameters and depths are also located in the central part of the Siersza deposit.

Of all the sinkholes registered, a total of 131 created or became active after 2011/2014. DDTMs analyses show that 20 sinkholes formed or activated between 2011/2014 and 2019, resulting in ground collapse with a total volume of over 257 m^3; between 2019 and 2022, 55 sinkholes formed (~2836 m^3), and between 2022 and 2023, there were 23 (~1800 m^3; Fig. 10). The formation of new sinkholes or reactivation of old forms occurred mainly in the central region of the deposit, i.e. where the highest density of sinkholes is found. Numerous sinkholes that formed in the last analyzed period were quickly backfilled, so that most of these changes were not recorded on the differential terrain models, though some of those were successfully recorded by TLS. Therefore, the volume of the collapsed ground is underestimated. Some of the forms visible on the DDTMs (especially for the period 2022–2023) were not confirmed during fieldwork. These were the result of DTM errors due to a small number of points representing the ground in areas of dense vegetation or artificial excavation. Information about the other sinkholes formed or activated after 2011/2014 comes from media reports and orthophotomap analyses.

DTM and DDTM analyses, as well as media reports of sinkholes in Trzebinia, indicated a significant threat to the central part of the study area, in the Jana Pawła II Street area. Aerial photographs from 1957 reveal that both the sinkhole in the cemetery and a number of sinkholes in the allotments that formed in 2022, are in fact reactivated old forms which had been backfilled. A review of the documentation prepared for the decommissioning of the Siersza mine indicates that the sink-

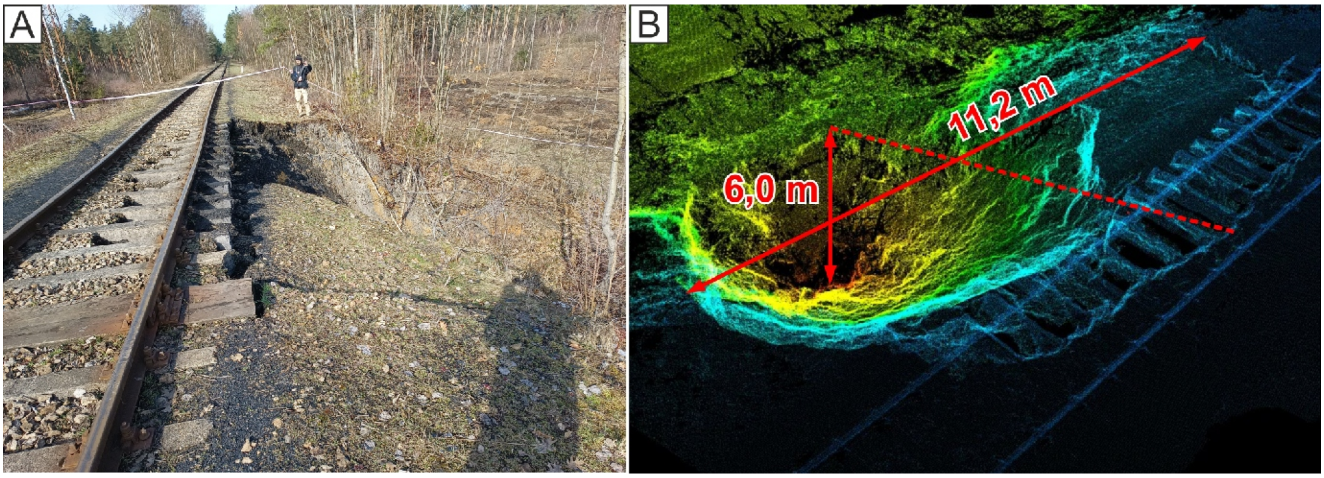

Fig. 8. Sinkhole in railway embankment

A – photograph taken during fieldwork; **B** – TLS point cloud visualization

holes that formed in the vicinity of Gaj estate in 2023 are also reactivated forms that originally formed in 1959. Hence, we analysed all available documentation including old aerial photographs, for the occurrence of sinkholes not visible at present. All data analysed indicate that at least 16 sinkholes backfilled in the past have been reactivated, representing 19% of sinkholes active after 2011/2014.

The areas of possible reactivation of old backfilled forms were primarily determined based on old aerial photograph analyses. Consequently, 161 sinkholes were identified in the study area. The vast majority of these are still expressed in the morphology, though located in forest terrain, outside of built-up areas and infrastructure. By comparing historical photographs, DTMs from the years 2011–2023 and fieldwork data, 52 areas were determined where sinkholes had been remediated (Fig. 11).

Areas with a high occurrence of remediated sinkholes include those near Młyńska Street, the area of the cemetery, and the area of the reclaimed mine dump. In the first area, seven sinkholes were identified, visible on an aerial photograph from 1957. The largest sinkholes occurred in the then-cultivated fields east of the field road (today's Młyńska Street; Fig. 12A). All the forms visible in the photograph were probably remediated by backfilling. They are located in the immediate vicinity of, or partly beneath, today's buildings. The form located farthest to the west is unclear. The photograph shows a distinct change of phototones in the form of a circle. Its diameter is similar to the sinkhole found on the eastern side of Młyńska Street. This indicates that either the sinkhole was initially present at that time, or that the area subsided after the sinkhole was later backfilled. However, during the stereoscopic analyses it was not possible to clearly identify subsidence at that location.

On the 1940s 1:1,000 scale mining maps, a sinkhole to the south of Młyńska Street was detected. As with the other forms in the area, it was possibly remediated by backfilling, as indicated by the lack of a sinkhole on the 1957 aerial photograph, and by the the area being in agricultural use at the time. Its location on the mining maps indicates that it was partly beneath the present residential building.

Another cluster of remediated sinkholes extends across the southern part of the cemetery, the allotments and a section of the railway embankment ~10 m high. Anthropogenic windrows dominate this cluster surface. Here the highest number of reactivated backfilled sinkholes has been recorded in recent years. This area is significantly transformed, with anthropogenic windrows dominating the surface. It is the area with the most significant intensification of sinkholes in recent years. It has seen the highest number of reactivated old backfilled sinkholes. Based on 1957 aerial photographs, 15 areas indicative of historical sinkholes have been determined (Fig. 12B).

The third area with a high density of sinkholes backfilled in the past is the currently reclaimed mining dump located to the northeast of Trentowiec estate. An examination of aerial photographs revealed the presence of several clearly visible sinkholes (Fig. 12C), which are currently covered by an approximately 10 m high embankment. No reactivation of backfilled sinkholes was found in the area, but two new forms were identified.

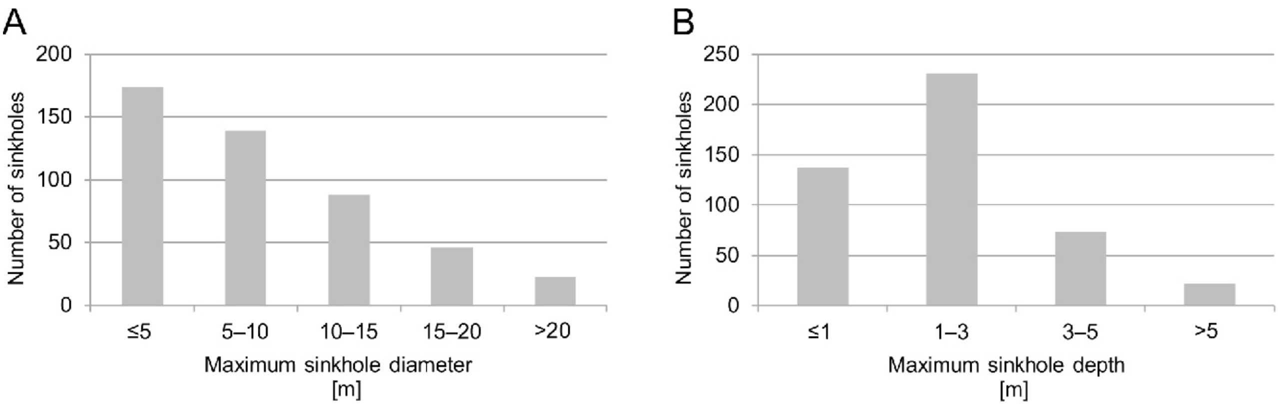

Fig. 9. Distribution of maximum diameter (A) and depth (B) of the sinkholes in the study area

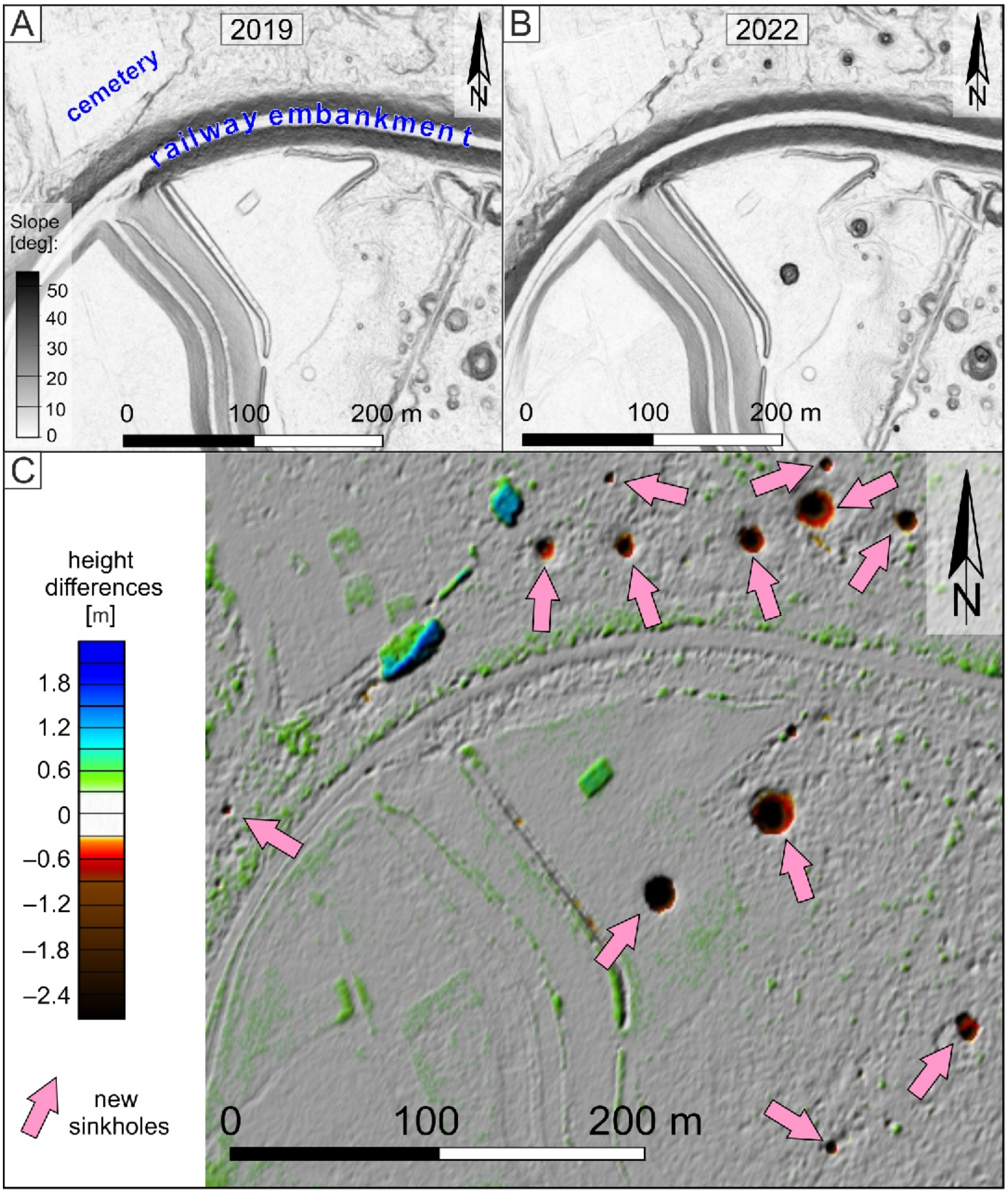

Fig. 10. Sinkholes within the cemetery area

A – ALS DTM recorded in 2019; **B** – ALS DTM recorded in 2022; **C** – DDTM 2022–2019

The majority (86%) of sinkholes catalogued in the area of the former "Siersza" Hard Coal mine influence are attributable to documented shallow hard coal deposits being mined to a depth of 100 m below ground level in seams 206, 207, 208, 209 and 209–210, 210, 214 and 301 (Fig. 11). These sinkholes are mainly located in areas of post-mining voids. Some are related to other elements of the mine infrastructure (galleries, ditches, etc.). Of the sinkholes documented, 10% occur in areas where coal was mined at greater depths. About 4% of the forms identified occur outside areas of documented coal mining. These sinkholes may be attributed to processes of natural suffosion, karst, or other human activity (e.g. sinkholes formed in places of abandoned old boreholes or excavations). Some of these recorded sinkholes may be due to historical, undocumented shallow coal mining.

Almost all sinkholes related to documented shallow mining and located in areas with post-mining voids are found in areas where coal was mined with the roof caving system. By contrast, no sinkholes have been recorded so far in areas of post-mining voids that were backfilled. A particularly high concentration of sinkholes is found in areas where at least two mined seams at different depths, not deeper than 100 m below ground level, are superposed.

All sinkholes studied are located where the thickness of overburden does not exceed 100 m. The vast majority (96%) are located where this thickness does not exceed 40 m (see Figs. 2 and 7). As regards overburden lithology, 88% of the sinkholes are located where the overburden comprises Quaternary deposits (sands, silts, weathered clays, windrows) or Carboniferous rock outcrops. The remaining sinkholes were

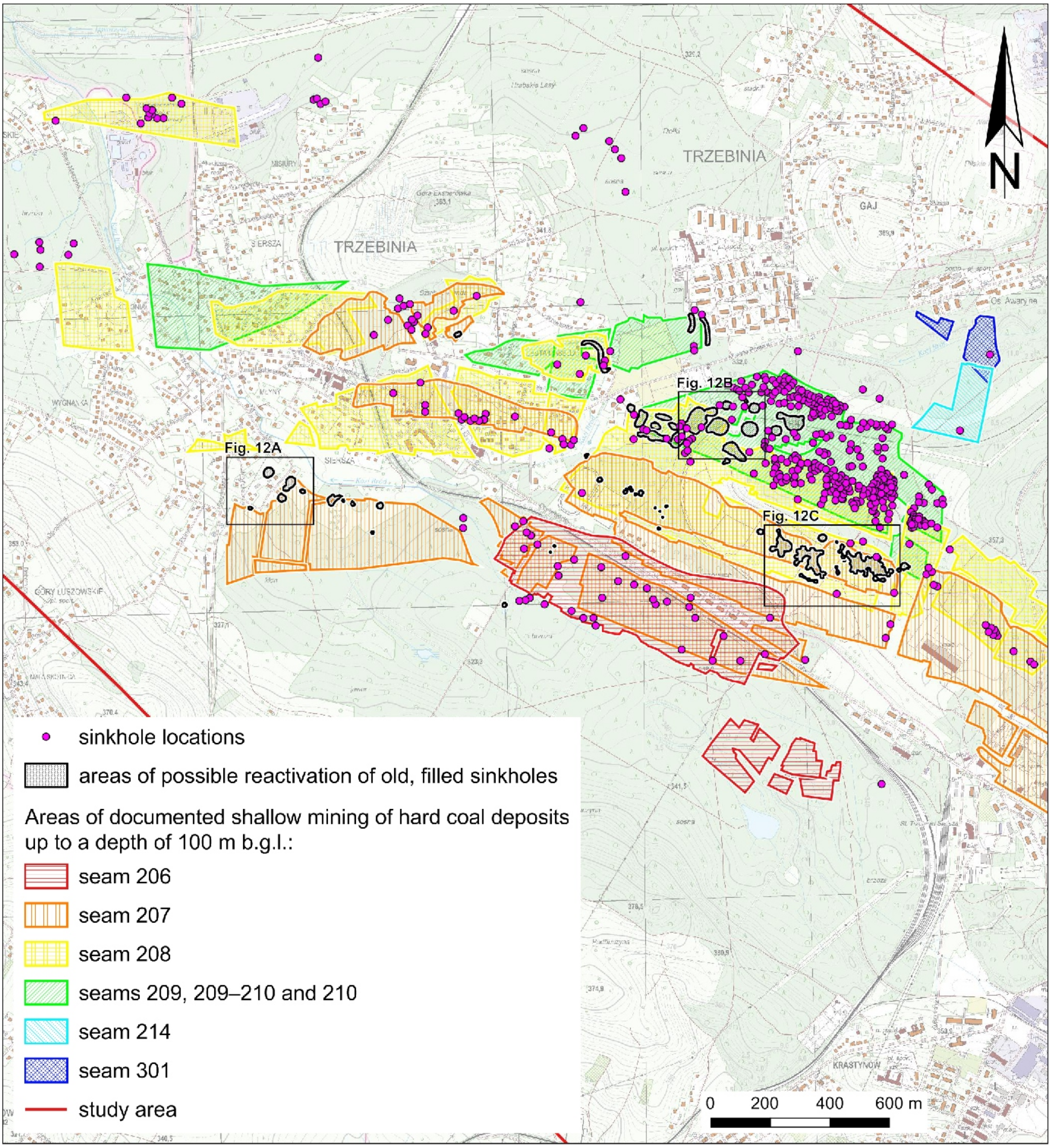

Fig. 11. The area of highest sinkhole density in relation to documented shallow exploitation

formed in places where the overburden consists of the Permian Myślachowice conglomerates (11%) and Triassic and Jurassic carbonate units (1%).

Based on these results, a VI-class sinkhole hazard map was made of the central part of the deposit (Fig. 13). The following factors were used to make the map, starting with the least important:

- a buffer from the boundary of shallow mining, covering mining areas to a depth of about 130 m;
- areas of sinkholes occurring outside the boundaries of shallow mining with a 20 m buffer;
- areas of shallow mining up to a depth of 100 m;
- areas of shallow mining up to a depth of 50 m;
- areas of former, remediated sinkholes;
- areas of shallow mining up to a depth of 100 m with a roof caving system;
- areas of shallow mining up to a depth of 100 m with at least two seams in vertical succession.

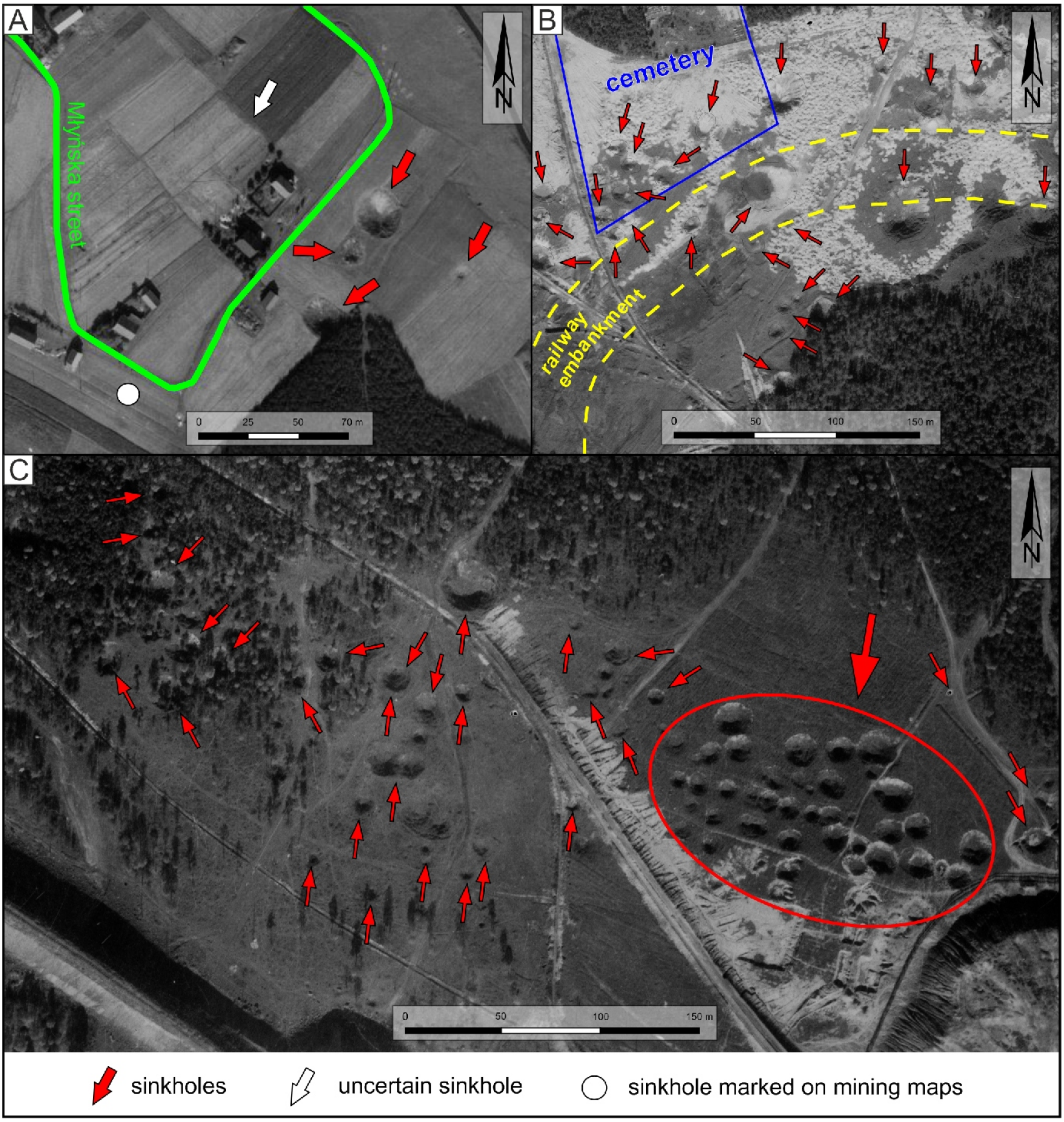

Fig. 12. Sinkholes visible on archival aerial photographs from 1957 year

A – area of Młyńska Street; **B** – area of the cemetery; **C** – Trentowiec estate area

The overlap of each factor increases the hazard by 1 class. The resulting map should be considered as an overview only.

CONTINUOUS DEFORMATIONS

A DDTM (DTM 2011/2014 – DTED 2) allowed determination of subsidence basins (Fig. 14). Minor subsidence with values up to -5 mm per year, mainly in the central part of the deposit, was also recorded after processing of data from 37 SAR images taken by the ERS track 451 satellite (data from 1993–2022) and ERS track 222 (data from 1992–2022). The subsidence trend can also be seen in the time series of changes for individual PS points (Fig. 15A).

In 2001/2002, there was a change in the motion vector from downwards to upwards, as seen in PSI data from Envisat satellite track 451 and 143 (2002–2010 data). In the central part of the study area, a group of points showing uplift with values of up to 14 mm per year can be seen (Fig. 15B). The change in the deformation vector from subsidence to uplift was constrained by two independent modes of processing for each period.

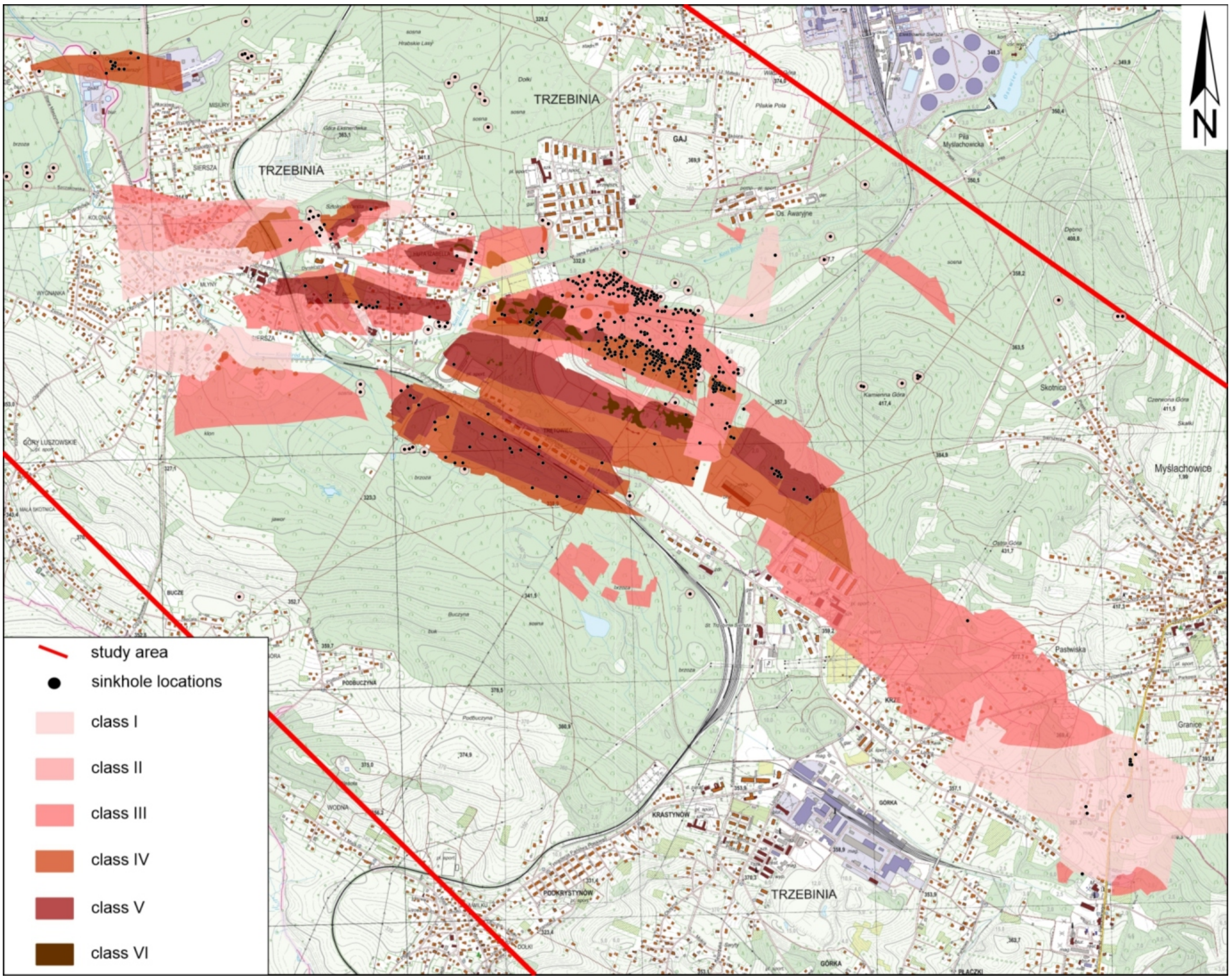

Fig. 13. Sinkhole hazard map of central part of the study area

A higher class value means a higher hazard

An analysis of contemporary InSAR data from the EGMS service for the period 2016–2021 and additional data Sentinel-1 processed independently for the year 2022 showed that minor uplift in the study area still exists and reaches values of up to 20 mm per year in the central part of the area (Fig. 15C).

Based on the PSI data, a map of contemporary continuous deformations in the study area was generated (Fig. 16). This map shows the average vertical displacement rates, on two information layers: (1) pixels with sides of 100 m, which correspond to the location of terrain units for which it was possible to identify PS points for both imaging geometries, and (2) linear contours interpolated from the point layer to the continuous surface, so as to fill in areas of missing data (where PS points were not recorded). The most precise data is from the 100 m pixel layer, as this is survey data, derived directly from EGMS data. However, for areas of low coherence, mainly forests, meadows and agricultural areas, where displacement information could not have been obtained from calculations, it was decided to supplement the measured data with an auxiliary layer derived from the interpolation of PS points.

DISCONTINUOUS DEFORMATIONS OF LINEAR TYPE

As a result of multi-temporal DTM analyses, archival documentation (Protokół Poinspekcyjny, 1997) and fieldwork, 254 linear-type discontinuous deformation structures were determined in the area of influence of the former "Siersza" Hard Coal Mine. The total length of the structures determined amounts to over 21 km. The most deformation structures of this type were found in the southeastern part of the area near Kowalikowa Mountain, west of Karniowice (Fig. 14). The first ones were already recorded between 1991 and 1999. Some structures were also described by Głogowska (2007). These structures are developed in the form of extensional fissures, suffosion trenches and thresholds (Fig. 17), along which sinkholes commonly develop. The opening of the extensional fissures is usually a few tens of centimetres. These forms occur mainly in sandstones. The width of the suffosion trenches is up to 5 m. They most often form within weak rocks that are susceptible to suffosion - mainly the Myślachowice conglomerates. Threshold heights generally do not exceed 1 m. Linear-type structures usually extend parallel to

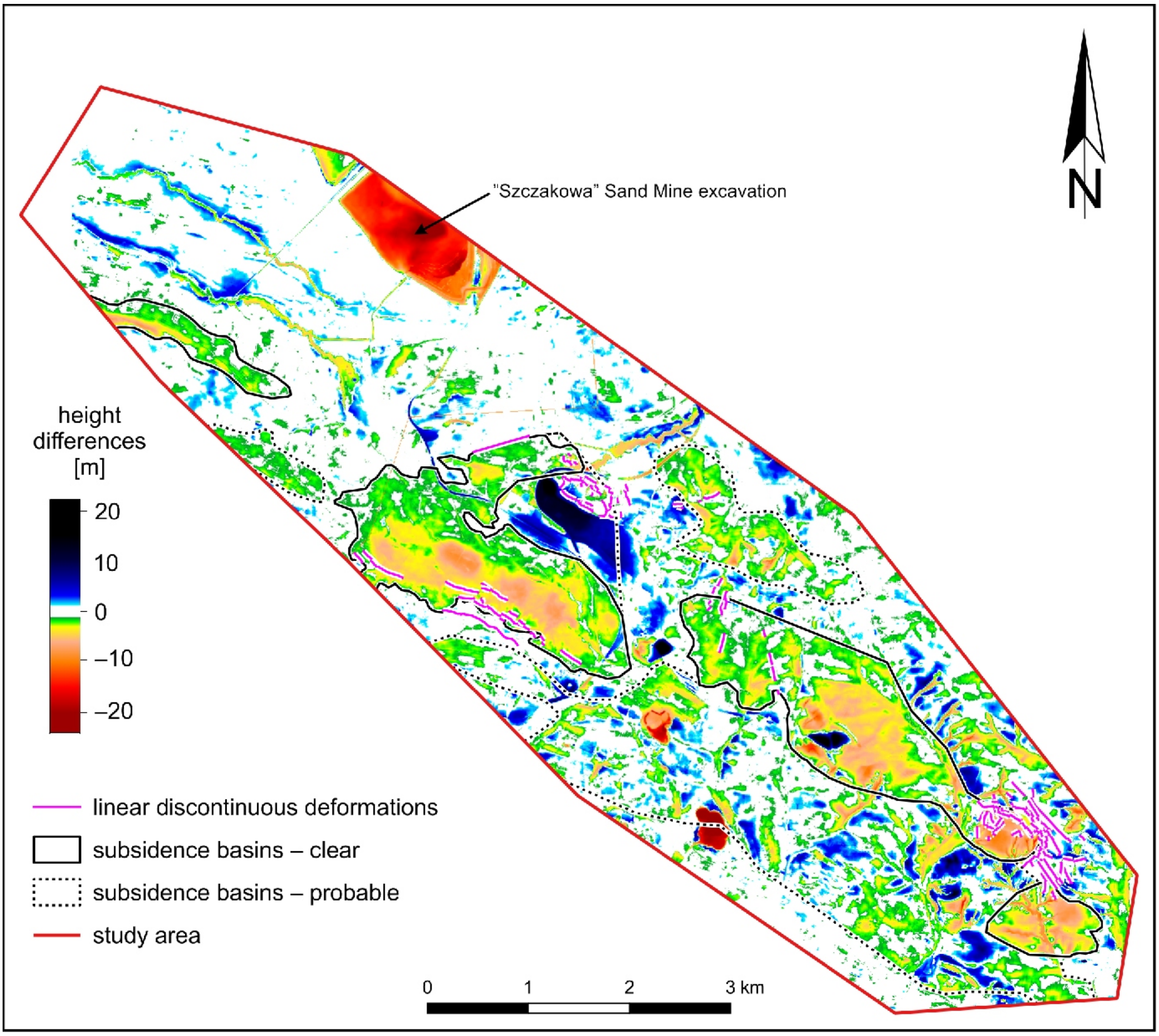

Fig. 14. Distribution of discontinuous deformations of linear type on a DDTM generated from DTM and DTED2 data

the Karniowice fault in the NW–SE direction, less frequently WNW–ENE, NE–SW to ENE–WSW and N–S. Deformation structures located on the summit of Kowalikowa Mountain coincide with the boundary of the subsidence basin (Fig. 14).

Another region with a high concentration of linear-type deformation structures is in the central part of the area, east of the railway embankment. The structures identified there relate to the edges of the pits along which the subsidence occurs. This subsidence correlates with the boundaries of the documented shallow mining of hard coal deposits by roof caving in seams 208 and 209–210. The area is dominated by structures with the character of fault sills that mostly show NW–SE extension, less frequently NE–SW and N–S.

A significant concentration of linear-type deformation structures of fault sill nature is also found in the southwest. These extend parallel to the nearby southern fault. The structures coincide with the edges of subsidence basins associated with coal mining by roof caving in the deeper (>100 m below ground level) seams.

DISCUSSION

With reference to archival data (Plewa et al., 2001), the results of the study demonstrate that the scale of post-mining discontinuous deformations in the area of influence of the former "Siersza" Hard Coal Mine has been underestimated. The intensification of sinkhole processes in the vicinity of buildings in the recent years resulted in the need for more detailed insight into the problem. The area studied is the first in Poland where post-mining deformations were demonstrated comprehensively using several remote and field methods.

The nearly 200-year mining tradition in the area, the existence of many companies (from as early as the 19th century) and the associated often incomplete transfer of old mining data to the documentation maps of the "Siersza" Hard Coal Mine resulted in limitations in the quality and accuracy of data regarding goafs. In the methods adopted so far for calculating the probability of sinkholes occurring in a given area, apart from the thickness of the overburden, important parameters were the depth

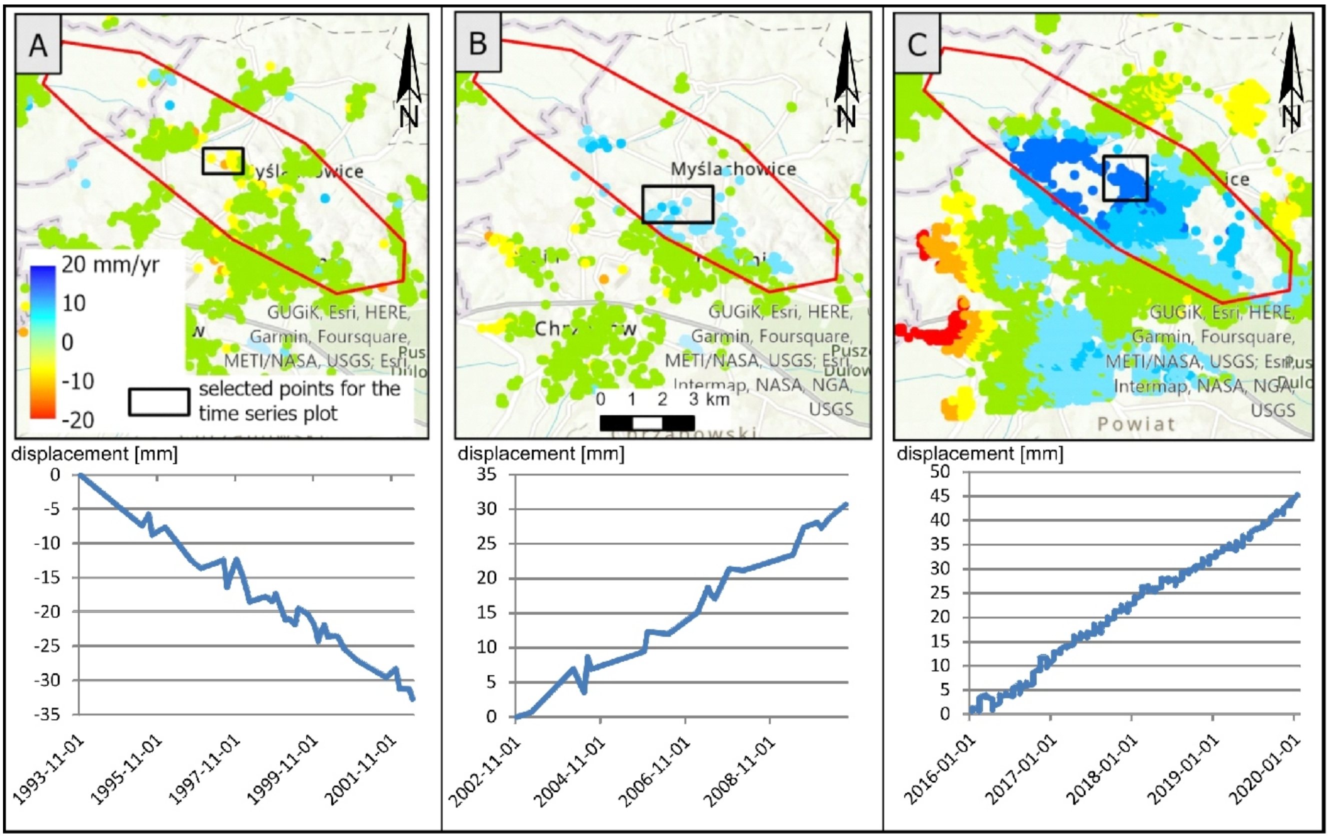

Fig. 15. The results of PSI processing for the study area

Colour scale of averaged PS velocity for all maps is shown on RYC A. The plots show time series of averaged PS velocity calculated for the black frame. **A** – PSI processing of ERS data (track 451), 1993–2002; **B** – PSI processing of Envisat data (track 451), 2002–2010; **C** – EGMS_L3 data (vertical component), 2016–2021

of the location of the void roof and its height (Chudek and Olaszowski, 1976). The height, width and volume of the void affect the deformation directly. In addition to these parameters, the physical-mechanical properties of the rocks are also important (Chudek et al., 1988). Unfortunately, for the area of the former "Siersza" Hard Coal Mine, in places of evident sinkholes on mining maps, there are many deficiencies in the marking of the parameters of the mine workings. This applies in particular to the seams (or their parts) with the earliest mining activity. The data is often limited only to the extent of the workings together with the designation of the system and years of mining. Therefore, the basis for assessing the risk of post-mining deformations in the study area was their comprehensive mapping and identification of similarities in deformed areas on the basis of the available geological and mining data.

A highly effective method of determining discontinuous deformation in the study area was to analyse multi-temporal ALS and ULS data. The identification of sinkhole areas using DTMs is well-known worldwide and has been successfully applied in recent years for both karst sinkholes (e.g., Filin et al., 2011; Zhu et al., 2014; Wu et al., 2016; Kim et al., 2019) and post-mining sinkholes (e.g., Suh and Choi 2017; Marian and Onica, 2021; Zheng et al., 2022; Yang et al., 2023). When the effects are intense, as was the case in Trzebinia, acquiring up-to-date imaging of the ground surface is an important element. One of the fastest methods is to perform laser scanning using a UAV. This method is more cost-effective than ALS, and increasingly available and effective. As with ALS, the accuracy of ULS data is dependent on land cover and, in particular, on vegetation (Briese, 2010; Ismail et al., 2015). For the area of influence of the former "Siersza" Hard Coal Mine, UAV scanning was performed between May and June. Laser beam reflections from dense vegetation resulted in local misclassification of points representing the ground, so that many potential sinkholes identified on the DTM were not detected in the field. The most favourable season for laser scanning appears to be early spring (after the snow cover has disappeared) and late autumn.

Most sinkholes documented in the area of influence of the former "Siersza" Hard Coal Mine are related to reactivation of old goafs up to 100 m below ground level. There is a clear correlation between the mining system, the amount of mined shallow coal seams and the number of contemporary and historical sinkholes. The number of sinkholes increases in areas where, in the past, two or more seams were exploited at depths of up to 100 m below ground level. Due to current land use, the areas most at risk are around Górnicza Street and Grunwaldzka Street, Odkrywkowa Street, the stadium and the southern part of the allotment gardens. Mining of two superposed seams has also occurred in the area of Zwycięstwa Street and Chrobrego Street. The risk there appears to be less significant due to the backfill mining system.

Analyses have shown that 10% of the sinkholes registered occur in areas where coal mining was carried out at depths greater than 100 m below ground level. So far, sinkholes in the USCB have been assumed to be mainly affected by mining at depths of up to 100 m below ground level (Chudek et al., 1988),

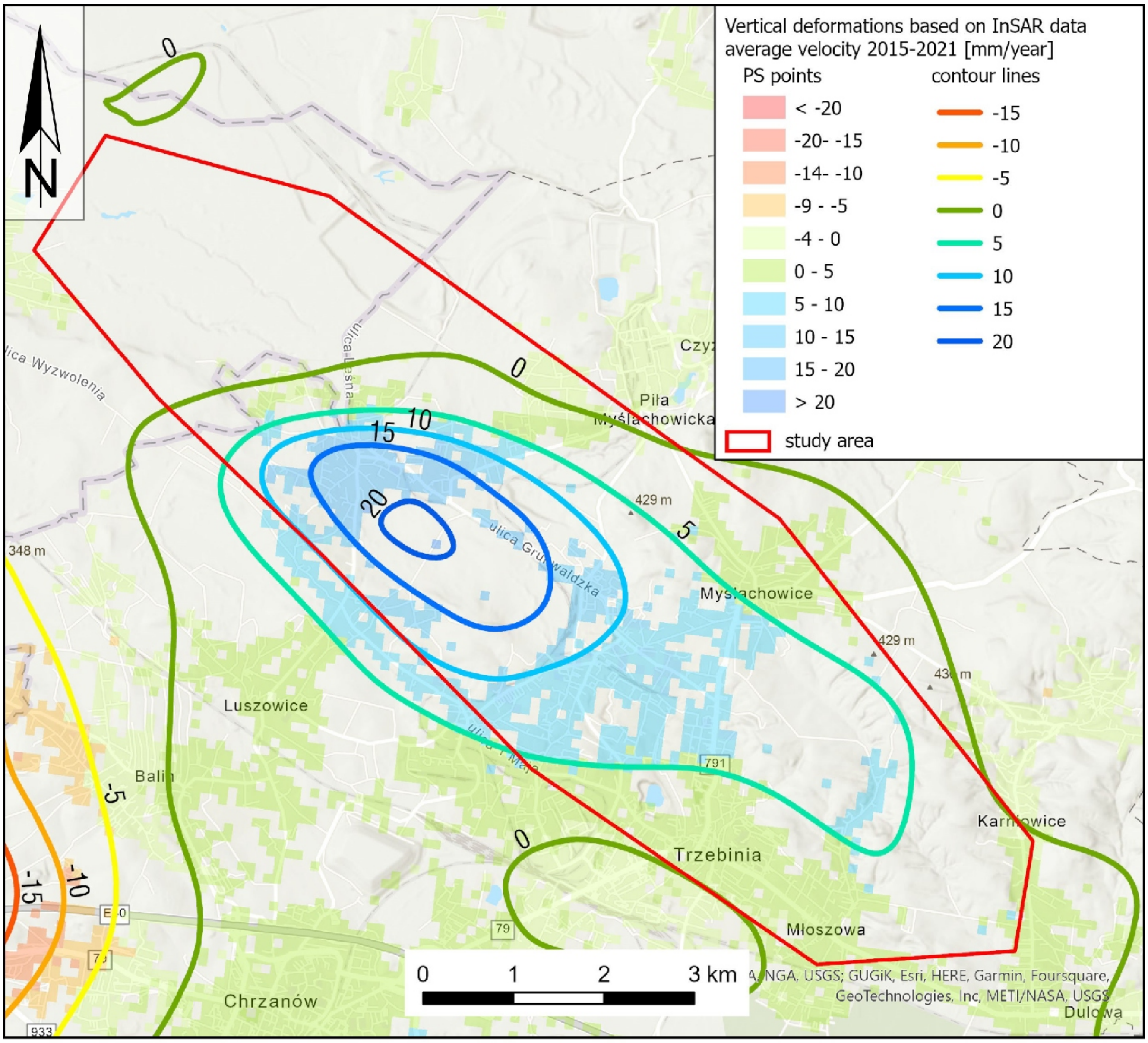

Fig. 16. Map of vertical displacement of the terrain surface within the study area based on EGMS InSAr data

and in some cases up to 80 m below ground level (Chudek et al., 1988; Strzałkowski et al., 2021). Sinkholes in India, China and the UK have also been generated by workings located at depths of up to 100 m (Singh and Dhar, 1997). Some data from around the world indicates that discontinuous deformation is related to the exploitation of even shallower seams. For example, in the USA, in areas of former hard coal exploitation, sinkholes appear mainly where the overburden is <50 m thick (Whittaker and Reddish, 1993; Canbulat et al., 2017). Our findings demonstrate that for such a complex system of workings as the Siersza mine and the exploitation of different superposed seams in one area together with unfavorable overburden lithology (mainly sand), the 100 m limit may be an underestimate.

Development of sinkholes before 2019 was caused mainly by precipitation, which washed loose overburden into the collapsed mine workings. Studies show that the rate of sinkhole development has increased significantly after 2019, this being mainly related to the gradual rise in groundwater level with leaching of the base of the Quaternary sediments. In order to limit this phenomenon, the Mine Restructuring Company installed special deep-well pumps in May 2023 to maintain groundwater level.

One new problem, not yet discussed, is the reactivation of sinkholes that had been remediated. The data from Trzebinia area indicate that at least 16 sinkholes backfilled in the past have subsided again. The multi-temporal NMT data indicates that in the area of influence of the former "Siersza" Hard Coal Mine, 85 sinkholes (not visible on the 2011/2014 DTM) developed in the last decade. Therefore, nearly 19% of sinkholes were from reactivation of those backfilled in the past. This indicates the need to also include as hazardous the remediated sinkholes. The reactivation of old sinkholes depends on a number of factors, including the method of sinkhole remediation, lithology of the seam overburden, the water flow rate, the inclination of the exploited seam etc. The influence of the sinkhole remediation method on its reactivation was noted by Strzałkowski (2000), who stated that the filling of sinkholes only by sand is insufficient and he proposed filling sinkholes, and surrounding old empty mine workings, using purpose-designed materials. Strzałkowski and Strzałkowska (2023) suggested that the best mixture for filling shallow voids in the rock mass is a water-ash-cement mixture characterized by a strength appropriate to the strength of the rock mass surrounding the void. When remediating only sinkholes, the fraction of backfill mate-

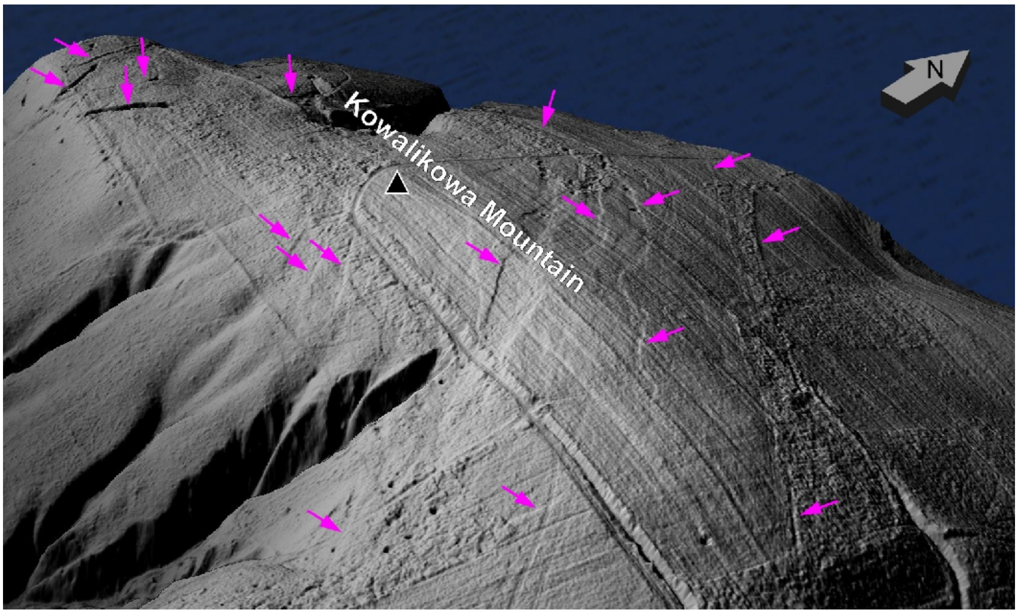

Fig. 17. Discontinuous deformation structures of linear type (marked by pink arrows) in the Karniowice area

DTM 3d view highlighted from azimuth 235 with altitude 30°

rial and compaction also seems to be important, larger rock fragments being more resistant to leaching. The rate of leaching of the material filling a sinkhole may increase with the slope of exploited seams. A greater inclination of the seams allows faster migration of the material particles filling the sinkhole. Reactivation of old sinkholes was found mainly in the area of the cemetery, the southern part of the allotments, the railway embankment, the Gaj estate, near Odkrywkowa Street and the southern part of Myślachowice (area of the 791 road). In case of the railway embankment, the danger comes from not only the reactivation of sinkholes in its body, but also from reactivation in its base. Due to the steep slopes of the embankment, such sinkholes may cause landslides. During fieldwork, a small slide above a reactivated sinkhole in the lower part of the embankment was observed.

The results of analyses of satellite data revealed a reversal of the deformation trend from subsidence, during the operation of the mine, to uplift after its closure. Such reversal of deformation associated with mining is well known and is usually associated with mine decommissioning by flooding, when water floods the excavated workings (Didier et al., 2008). Recorded cases of uplift after flooding of underground mines are known for example from Wałbrzych, where large uplift values were recorded in particular in the near-slope areas (Blachowski et al., 2009), from GZW – the "Czeczott" mine area (Strozik et al., 2016), from the German-French border area (Samsonov et al., 2013) and from a coal mine at Houthalen in Belgium (Verwoort, 2016). In the last case this process of uplift was associated with the swelling of the clay minerals in rocks of the coal strata after the flooding of the underground workings. In the case of the Siersza mine, the proportion of clay minerals in the rock mass is low, as is the impact of swelling. A greater role in uplift overall is played by the build-up of hydraulic pressures in the rock mass. Namjesnik et al. (2022) highlighted the possibility of fault reactivation as a result of stress perturbations related to mine decommissioning by flooding. For Trzebinia, the area of greatest subsidence is bounded by the Siersza and South faults. The present slow uplift of the area coincides broadly with the subsidence basin, with the highest values observed in the central part of the deposit and not in the boundary area of the basin (near the fault).

CONCLUSIONS

Problematic sinkholes have long existed in the study area. The vast majority of the historical sinkholes were formed before 1957, the time when the oldest analysed aerial photographs of the area were taken. Many of them may have been established as early as the 19th and early 20th centuries, when coal was mined at depths usually not exceeding 50 m below ground level. The largest sinkhole in Siersza is located in the old bed of the Kozi Bród stream and was associated with disastrous incursion of surface water into the mine in 1922 (Pietraszek, 1961).

Comprehensive research into deformation in the area of influence of the former "Siersza" Hard Coal Mine has allowed broad assessment of the hazards in this area. This is the first research area in Poland of discontinuous terrain deformation where all possible methods for detecting changes in the terrain surface have been applied. This comprehensive approach resulted in accurate description of the scale of geohazards present and identification of the areas at risk. The comprehensive mapping together with the analysis of the geological and mining factors made it possible to come to the following conclusions, as presented in a report to the Polish Ministry of the Environment (Wojciechowski et al., 2023).

The major cause of sinkhole formation in the area of influence of the former "Siersza" Hard Coal Mine is the presence of shallow goafs, formed as a result of shallow coal mining to a depth of 100 m below ground level. Factors promoting the formation of new sinkholes, or reactivation of existing ones, are the rising groundwater table and increased water infiltration as a result of intense or prolonged rainfall.

DTM differential analyses demonstrate that the sinkhole development rate increased significantly after 2019. In the period from 2019 to 2023, it was several times higher than in the previous years, this being attributable to the rising groundwater table, which eliminated the cone of depression.

The greatest concentration of sinkholes is found in areas where Quaternary deposits (mainly sands) or anthropogenic deposits dominate the overburden and are <40 m in thickness. This also applies to sinkholes newly formed or reactivated after 2011/2014.

Most sinkholes were created in the central part of the area, from shallow mining of seams 206, 208, 209–210, in particular where the depth of mining did not exceed 50 m below ground level and in places where the mining was deeper (about 100 m below ground level) and where two seams were superposed. An additional factor that increases the risk is the exploitation system. The most hazardous areas are those of shallow coal mining that used the roof caving system. Such areas may continue to be at risk of new sinkholes. Due to the mining and decommissioning system applied and the small thickness of the overburden (not exceeding 20 m), the risk of these phenomena may also concern the extreme southeastern part of the deposit, west of Karniowice.

Based on the comprehensive mapping of sinkholes, it is inferred that old sinkholes, which had been backfilled, may also pose a threat. Nearly 19% of sinkholes that occurred after 2011 involved reactivation of old ones.

Many sinkholes occur in areas of documented coal exploitation at greater depths than 100 m below ground level. This suggests that even such deep and complex mine workings, as in the former "Siersza" Hard Coal Mine, may contribute to the formation of sinkholes.

Due to the increased development of sinkholes in recent years and their formation also outside the areas of shallow mining, systematic monitoring of the ground surface, e.g. with the use of aerial laser scanning or UAV, is recommended. This will allow the onset of the phenomena to be assessed in the future and the effectiveness of the measures taken to reduce the risk of deformation in Trzebinia area to be evaluated.

The processing of archival SAR data made it possible to trace the development of continuous deformation in the study area from 1993 to 2022. It was found that the area covered by the "Siersza" mine area was subjected to constant, minor subsidence with values of up to –5 mm/year at its centre. In 2001/2002 there was a change in the vector of movement from downwards to upwards. At present, the area of the "Siersza" mine is subject to constant, minor upwards movements at a rate of up to ~20 mm/year in its centre. The change in from downwards to upwards movement occurred at about the same time as coal mining was discontinued and the mine was closed. The slow uplift of the ground surface is associated with the build-up of hydraulic pressures in the rock mass.

Discontinuous deformation structures of linear type in the area of influence of the former "Siersza" Hard Coal Mine are related mostly to the documented mining of hard coal deposits at various depths with the roof caving system. These are fault sills and extensional fissures which have locally transformed into suffosion trenches, in particular where the Myślachowice conglomerates, susceptible to erosion, occur in the overburden.

The linear structures are mostly in line with the course of some of the faults bounding the mining pits and replicate their course to the ground surface. They are also parallel to the boundaries of shallow workings or relate to the boundaries of subsidence basins related to the mining of deeper seams.

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