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ORIGINAL PAPER

APPLICATION OF SATELLITE RADAR INTERFEROMETRY (PSInSAR) IN ANALYSIS OF SECONDARY SURFACE DEFORMATIONS IN MINING AREAS. CASE STUDIES FROM CZECH REPUBLIC AND POLAND

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ABSTRACT

Secondary deformations are ground movements occurring in areas of ceased underground mining. These are associated with delayed readjustment of rock mass resulting in subsidence, discontinuous deformations (sinks, cracks, etc.) due to destruction of underground, usually shallow, workings, and elevation of ground surface in response of rock mass to rising groundwater levels following the end of mine water drainage. Comparative analysis of secondary deformations in two former mining areas in the first period after cessation of underground hard coal mining is the subject of this study. We used ERS-1/2 and Envisat satellite radar interferometry data processed with PSInSAR technique and GIS to map vertical (in satellite's line of sight, LOS) movements of the surface and analyse them in relation to location of coal fields and underground water table rise. In the study, two areas have been compared, the *Ostrava* city in the *Czech* part of the *Upper Silesian Basin* and the *Wałbrzych Coal Basin* in *Poland*. The results of analyses based on the results of PSInSAR processing between 1995 and 2000 for the *Wałbrzych* site indicate uplift (up to +12 mm/year) in closed parts of coal fields and subsidence (up to –8 mm/year) in areas of declining mining. Results of PSInSAR analysis over the *Ostrava* site indicate decaying subsidence after mine closures in the rate of up to -6 mm/year during 1995-2000. Residual subsidence and gentle uplift have been partly identified at surroundings of closed mines in *Ostrava* from 2003-2010 Envisat data. In *Wałbrzych* gentle elevation has been determined from 2002 to 2009 in areas previously subsiding.

INTRODUCTION

Surface movements in underground mining areas, e.g. hard coal mines, that appear after the end of mining activity are known as secondary deformations (Chwastek, 1980; Chudek, 2002). These deformations are most often associated with delayed readjustment of overlying rock mass resulting in residual subsidence, sudden destruction of underground, usually shallow, workings, which may result in discontinuous deformations on the surface (e.g.: cracks, fissures, sinkholes) and elevation of ground surface that is the effect of response of rock mass to the rising groundwater levels following the end of mine water drainage.

Satellite radar interferometry (InSAR) is now a well-established technique for monitoring ground surface movements that is capable of surveying large areas at a competitive cost and comparable precision compared to other techniques (e.g. levelling and GNSS measurements). A significant advantage of InSAR is that satellite radar images are collected continually and allow to look back and analyse historical ground movements. Various interferometric techniques have already been applied to study surface changes related to both active and inactive underground hard coal mining. Notable applications of SAR interferometry in studies of secondary deformations in post-mining areas have been described by Abdikan et al. (2014), Bateson et al. (2015), Caro-Cuenca et al. (2013), Gee et al. (2017), Mei et al. (2007), Raucoules et al. (2007), and Samsonov et al. (2013), among others. These examples show the scope of InSAR applications for mining related ground movement studies that include application of a variety of SAR sensors, different processing techniques, different mining sites, and diverse goals of these studies.

In Abdikan et al. (2014), 18 SAR images acquired between 2007 and 2010 by the Japanese Advanced Land Observing Satellite (ALOS) were used to map surface movements using the Persistent Scatterer Satellite Radar Interferometry (PSInSAR) technique. The authors used Phased Array Type L-band Synthetic Aperture Radar (PALSAR) to determine if it can be successfully applied to identify mining deformation in rural and vegetated areas of

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Zonguldak, located along the Black Sea coast in the northwest of *Turkey*. They obtained a density of 218 PS/km^2 and observed subsidence rates between -30 and -40 mm/year for individual coalfields that showed correlation with volume of produced coal.

Bateson et al. (2015) concerns studies of ground surface movements in the *South Wales Coalfield* in *United Kingdom* where 55 ERS-1/2 SAR C-band images for the period between 1992 and 1999 were used and processed with the ISBAS (Intermittent Small BAseline Subset) technique. Most of underground mines in this area closed in 1990's. The authors claimed that the applied technique provided better target density than SBAS and PS techniques, and established a large area of uplift with rates of up to 10 mm/year. The uplift was attributed to mine water rebound following the closure of mines and the end of pumping activity that allowed the water levels to return to equilibrium.

Caro-Cuenca et al. (2013) described results of a surface deformation study in an area of abandoned coal mines in *Limburg* (*the Netherlands*) and neighbouring countries (*Belgium* and *Germany*) carried out with PSInSAR technique. The authors determined the character of surface deformations following closedown of coal mines in 1994 for the study period from 1992 to 2009. They attributed the calculated uplift of up to 220 mm for the mines in *Belgium* and up to 125 mm in the *Dutch* part of the study area to rising groundwater levels following the end of mine water drainage. They observed correlation between varied rates of ground uplift and changing water levels in individual coal fields forming water-basins separated by faults.

Gee et al. (2017) followed their earlier investigations on abandoned coal fields in the *United Kingdom* (*NE England*) using the Intermittent Small Baseline Subset (ISBAS) DInSAR technique on ERS-1/2, Envisat, and Sentinel-1 SAR images. They observed uplift of the ground attributed to increases in pore pressure in the rock mass following the cessation of groundwater pumping after mine closure. They have also identified regional differences in the rate of uplift caused by local geological settings (faults).

The study by Mei et al. (2007) was aimed at mapping and monitoring mines that had operated in Alberta (Canada) through late 1800's and 1900's and closed prior to 1975. The authors tried to locate and document precise sites of underground workings (adits and shafts) where only general locations of former mines were known. The authors used data acquired between 2004 and 2006 by the Canadian Radarsat-1 satellite and determined subsidence of up to -3.2 mm/year above two abandoned mines. It was the first attempt at monitoring ground deformation in this area where occurrences of surface collapse associated with destruction of old underground workings were mitigated on a case by case basis.

Raucoules et al. (2007) used conventional SAR interferometry in the coal-mining basin of *Lorraine* (*France*) for historical assessment of surface deformation using C-band (ERS-1 data) and L-band (JERS-1 data). The latter was being used as a complementary tool to the C-band interferometry in a test area that was covered by forests and urban settlements.

The coal mining area on the *French-German* border has been also studied by Samsonov et al. (2013) who used 167 SAR ERS-1/2 and Envisat images acquired between 1995 and 2009 from one ascending and one descending track and created over five hundred interferograms that were used for time series analysis. This approach allowed to detect temporal variability of surface deformations, i.e. reversal from subsidence to uplift. The authors determined that deformation rate changes were mainly caused by water level variations in the former mines.

These selected examples prove that currently a range of payable and free of charge sources of satellite radar images are available and numerous processing techniques have been developed and successfully applied to study short and long term surface movements in areas of ceased underground mining activity.

In this paper, we aim at comparing research approaches applied by two different teams located in the *Czech Republic* and in *Poland*. The subject of our study is the quantification and the comparative analysis of secondary deformations in two former hard coal mining sites where mining finished in 1990's. The first, the ***Ostrava* site** is located in the *Czech* part of the *Upper Silesian Coal Basin*, and not far from still active mines in the vicinity of *Karviná*. The post-mining city of *Ostrava* is the third largest city in the *Czech Republic* with 300 000 inhabitants. The other, the ***Wałbrzych* site** lies in the *Central Sudetes* Mts. with coal-bearing deposits situated in the *Lower Silesian Coal Basin*. The *Polish* city of *Wałbrzych* with a population of over 100 000 has gone through the de-industrialisation processes similar to *Ostrava* (Fig. 1).

The authors started their studies in both sites independently. Milczarek et al. (2017) applied Envisat data and the PSInSAR technique to determine ground movements in urbanised parts of Wałbrzych for 9/2002 – 7/2009 period. The results indicated an uplift of the surface within boundaries of former mining areas of up to 6 mm/year and on average 4 mm/year. On the other hand, Jiránková and Lazecký (2016) applied the Quasi Permanent Scatterers InSAR (Quasi-PS InSAR) technique to TerraSAR-X satellite images to investigate ground movements (subsidence) in the active part of the *Ostrava-Karviná* coalfield between 10/2013 and 5/2015.

In this study, we use the Permanent Scatterer InSAR technique and ERS-1/2, as well as Envisat satellite data to study and assess the character of ground movements prior to the previously mentioned studies. We have analysed the final stage of mining and the first years after the end of underground

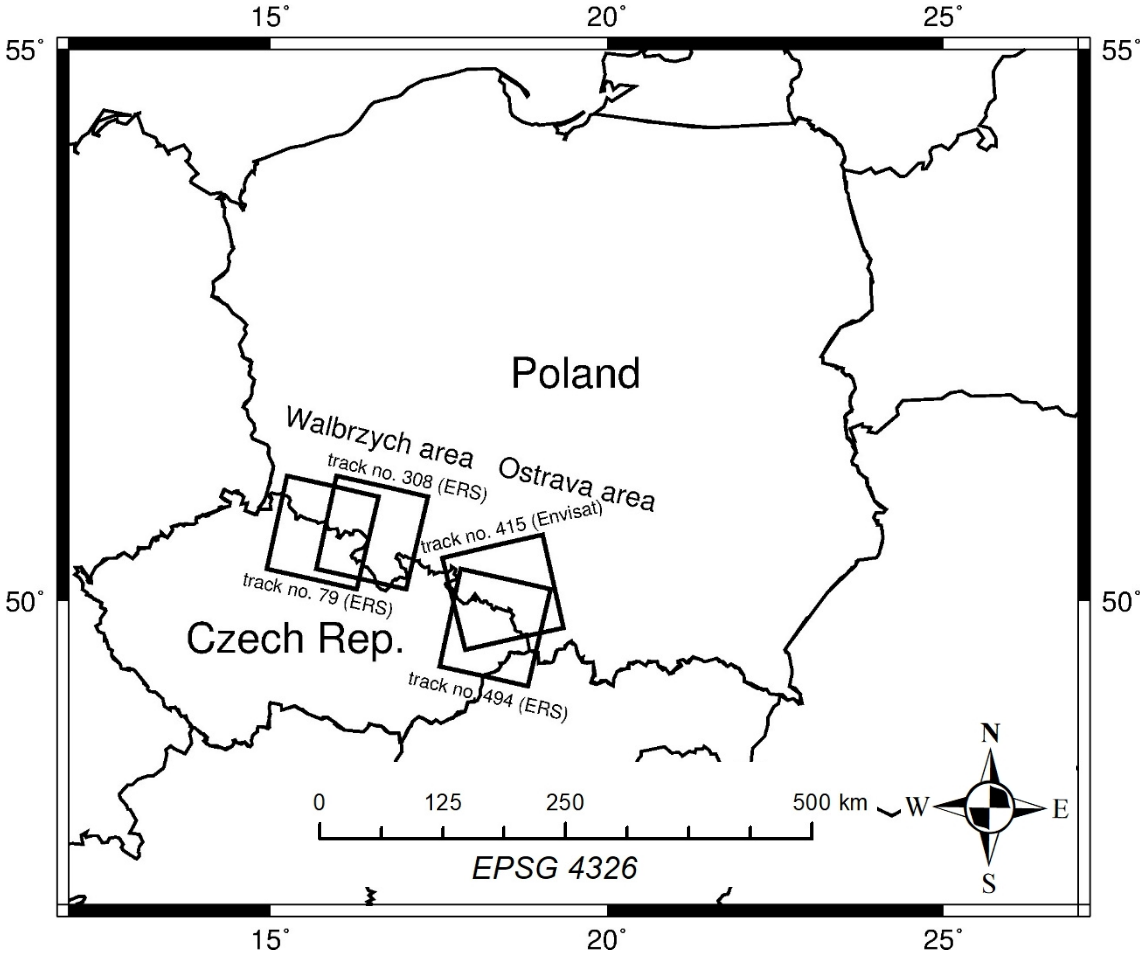

Fig. 1 Locations of study areas in the *Czech Republic* and in *Poland*.

operations at the *Ostrava* site (i.e. from 1995 to 2000, and from 2003 to 2010), as well as at the *Wałbrzych* site (i.e. from 1995 to 2000). .

Application of satellite data interferometry has allowed us to look back and obtain quantitative data for the analysis of surface movements related to underground mining in developed and built-up parts of these mining sites.

As a result, we have been able to compare the character of deformation process in two different former mining sites that have different geological and mining conditions, and correlate the observed deformations with areas of mining and underground water table rise after end of mine water drainage.

The structure of this paper consists of an introduction including brief literature review, further chapter on geology of the *Ostrava* (the *Czech Republic*) and the *Wałbrzych* (*Poland*) mining sites, a description of the PSInSAR processing methodology used in the study, and the analysis and discussion of results.

GEOLOGICAL AND MINING SETTINGS

Both the *Ostrava* (in the *Upper Silesian Coal Basin*) and the *Wałbrzych* (in the *Lower Silesian Coal Basin*) sites are situated in the coal basins spread over the border between the *Czech Republic* and *Poland* (Fig. 1). These coal basins originated from deposition of Carboniferous deposits in paralic and limnic environments.

THE OSTRAVA SITE

The Upper Silesian Coal Basin covers an area of 7 000 km^2 of which about 1550 km^2 are occupied by the coal-bearing Carboniferous in the territory of the *Czech Republic* (Dopita and Aust, 1997). West border of the basin passes from *Nový Jičín* in the direction towards *Hošťálkovice* to *Czech-Polish* state border and further continues to *Poland*. The borders to the south and south-east are not confirmed (Dopita and Aust, 1997).

In operational terms, the *Czech* part of the basin can be divided into *Ostrava-Karviná* area (also referred to as the *Ostrava-Karviná* coalfield) and the *Podbeskydská* oblast area.

The *Ostrava-Karviná* area is subdivided by the NNE striking *Orlová* structure into the western *Ostrava* part where mining finished in 1990’s and eastern *Karviná* part where mining still has been operating. The western *Ostrava* part is further split by

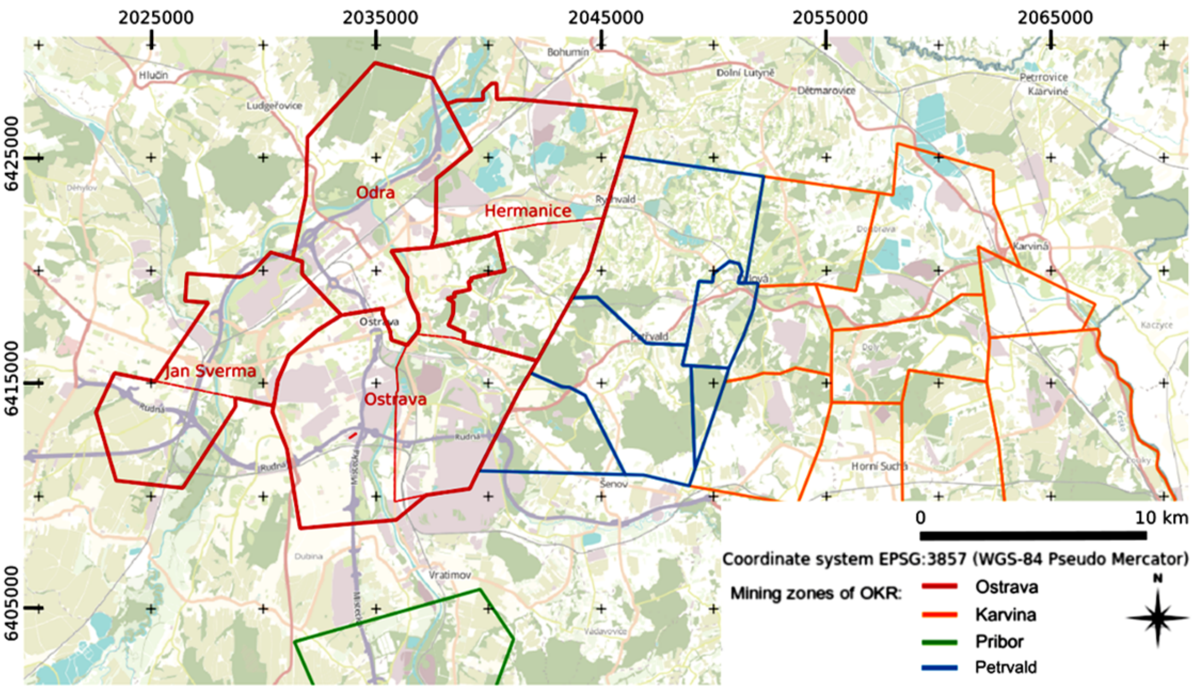

Fig. 2 Boundaries of former mining sites of the *Ostrava-Karviná* coalfield (including former mining sites at the *Příbor* area).

the *Michálkovice* structure. That operational division into three so-called sub-basins – *Ostrava*, *Petřvald,* and *Karviná* (taken from west to east) (see Fig. 2) enables us to describe the differences in these sub-basins in terms of the progress with mine closure, accompanied by decline of subsidence, and management of mine dewatering (see later in this section).

The other, the *Podbeskydská oblast* area is subdivided into 5 parts (*Příbor*, *Těšín*, *Mořkov*, *Frenštát*, and *Jablunkov*). The only mining works were performed in the *Příbor* area. In the *Frenštát* part, where the mining has been also taken under consideration, the coal exploitation did not occur yet (Majer et al., 1985).

Carboniferous deposits in the *Czech* part of *Upper Silesian Coal Basin* consists of the *Ostrava* Formation and the *Karviná* Formation on the top. The paralic *Ostrava* Formation consists of the *Petřkovice*, *Hrušov*, *Jaklovec*, and *Poruba* Members. The continental *Karviná* Formation consists of the Saddle, *Suchá*, and *Doubrava* Members. The Carboniferous is buried under overlying Tertiary and Quaternary sediments of variable volume and crops out sporadically in some places of the *Ostrava-Karviná* coalfield (e.g. in *Petřkovice*, *Ostrava*, *Petřvald*, *Orlová* and *Karviná*).

The *Ostrava* Formation is up to 3200 m thick, it contains more than 170 coal seams, with an average thickness of 73 cm. The *Karviná* Formation is up to 1000 m thick with up to about 90 coal seams. Average thickness is 180 cm per coal seam and the maximum thickness is 16 m for the lowest layer of the Saddle Member (Dopita and Kumpera, 1993). The amount of the seams and their thickness is reduced in the direction to the east and south in both of the formations. Both coal-bearing formations are built by claystones, siltstones, sandstones, conglomerates and coal beds. Sandstones and conglomerates are present mainly in basal part of *Karviná* Formation in the Saddle layers (Majer et al., 1985).

Two major tectonic directions take part on the structural-geological constitution of the *Upper Silesian* basin - the main lateral in the direction NNE-SSW and the transverse in the direction approximately W-E. In addition to that, the structure of the *Ostrava-Karviná* coalfield is characterized by two dominant tectonic styles to the west and to the east from the NNE-SSW striking *Orlová* structure. West of the *Orlová* structure prevails a more complicated, fold-fault style of the Variscan foredeep where the NNE-SSW direction is dominating, while the W-E direction is less frequent. On the contrary, east of the *Orlová* structure the subhorizontal strata and a predominance of normal fault systems are typical with prevailing W-E structural direction. However, the N-S structural direction is still pronounced (Dopita and Aust, 1997). The most significant tectonic faults reach even several hundreds of meters of elevation difference (Majer, 1985).

In the final stage of mining activities in the *Ostrava* sub-basin (1991-1994), all the *Ostrava* mines were divided into four organizational units on total area of about 110 km^2 – the *Odra* (NW of the *Ostrava city*), *Heřmanice* (NE), *Jan Šverma* (SW) and *Ostrava* mines (SE and the city centre). The *Czech* government called a cessation of mining works in the *Ostrava* city in two phases (1991-1992 and 1993-1996), therefore mining activities stopped gradually. Mining finished in March 1992 at the *Jan Šverma* mine, in December 1992 at the *Ostrava* mine, in June 1993 at the *Heřmanice* mine and on 30th June 1994 at the *Odra* mine. After that, all four mines were merged into one, the *Odra* mine (Černý, 2003). Since then abandoned mines in the *Ostrava* city have been taken care of.

In the *Petřvald* sub-basin, mining finished in February 1998. Excavation in the *Paskov* mine in the *Příbor* part (to the south of *Ostrava*) ended in April 2017. Coal excavation is currently performed in the *Karviná* sub-basin. Seven mining areas of about 80 km^2 are in charge of two active mines: Mine Plant 1 (merged previous the ČSA, the *Lazy* and the *Darkov* mines) and Mine Plant 2 (former the ČSM mine).

In the *Ostrava* subbasin, terminating of mine dewatering, which had been associated with coal mining for hundreds of years, started in 1995. The termination ended in 1997. Natural influx of water subsequently caused gradual flooding of mines. However, the *Ostrava* sub-basin is connected by a network of underground man-made structures through the *Petřvald* sub-basin with the *Karviná* sub-basin where mining is still in progress. Therefore, regulation and drainage of an excess of underground mine water from the *Ostrava* sub-basin have been performing by means of the *Jeremenko Water Shaft* from 2001. Mine water is maintained at the level of about -390 m a.s.l. at this shaft that corresponds to about 600 metres below the surface. Flooding level in other parts of the *Ostrava* sub-basin differs from site to site given the *existence* of separated water reservoirs (Rapantová and Grmela, 2004). In the Karviná sub-basin mine water level is kept lower than 1100 m below the surface.

THE WABRZYCH SITE

The Wałbrzych Coal Basin together with the *Nowa Ruda* Coal Basin form the Lower Silesian Coal Basin associated with hard coal deposits in *Czech* and the *Polish Sudety Mts*. Coal-bearing layers in the *Wałbrzych* area are associated with three of the four lithostratigraphic Pennsylvanian complexes: the *Žacléř*, *Biały Kamień*, and *Wałbrzych* formations. Altogether, 80 coal seams have been identified, including 48 in the *Žacléř* Formation and 30 in the *Wałbrzych* Formation. The productive coal levels varied in thickness from less than 1 m to over 2 m. The stratal dips of geological layers are towards the centre of two basins, *Sobięcin* and *Gorce*, that are separated by intrusion of the *Chełmiec* Mountain. Inclination varies from several to over 30 degrees, and from 30 degrees to 60 degrees in the basin edges. The complicated geological structure is the product of intrusive and compressive tectonic activity. The throws of the main faults reaches up to 300 m. In addition, there are numerous local faults, with throws of several metres (Kominowski, 2000).

The area of former mines in Wałbrzych covers approximately 94 km^2 (Fig. 3). It is situated in the southern part of the *Wałbrzych* Mts., in intra-mountainous depressions of the *Central Sudetes* Mts.. The region has assorted topography with wooded hills, Mt. *Chelmiec* (851 m a.s.l.) being the highest one, separated by elongated valleys. Coal mining caused transformations of the original topography such as development of subsidence basins and construction of anthropogenic landforms e.g. settlement ponds and waste dumps. The latter, reaching up to 100 m above the ground, are sometimes larger in size than the neighbouring natural landforms. Terrain elevation differences are up to 350 m (Wójcik, 2008).

The beginning of coal mining in Wałbrzych dates back to the second half of the 14th Century. At that time, coal was mined from the surface. With the progress of time, underground methods were introduced and coal production intensified. In the second half of the 19th Century, mining of coalfields located under settlements and linear infrastructure (roads, railways, etc.) began. After World War II, coal production peaked in 1955 with production of 3 250 thousand tonnes, later on the values oscillated around 2 500 thousand tonnes per year. Mining in three mines: *Thorez/Julia*, *Victoria*, and *Wałbrzych*, that operated after 1945 gradually, diminished between 1990 and 1998. The *Polish* government started cessation of mining works in the Wałbrzych Coal Basin from the end of 1990. The steady drop in coal production was accompanied by controlled flooding of underground workings through controlled decrease in mine water drainage of the rock mass. The process of mine flooding was started in 1994 and because of favourable geological settings particular mines were flooded independently. The sequence of flooding the mines was as follows: The *Witold-Barbara* water basin associated with part of the *Victoria* mine filled between 1994 and 1999, the *Pokój* water basin associated with part of *Thorez/Julia* mine filled between 1995 and 1997. The *Victoria-Chrobry* water basin in the central part where mining continued was filled partly between 1994 and 1998 and completely from 1998 to 2002, the restoration of groundwater table in *Julia* basin occurred approx. at the same time. (Fiszer and Gogolewska, 2003). Boundaries of water basins and boundaries of coal mines have been shown in Figure 6 in the Results part.

Results of studies, based on processing benchmark heights from two precise levelling campaigns have shown differentiated vertical movements ranging from -0.048 m to +0.189 m after the end of mining (1993-2014) indicating present-day secondary movements on these grounds (Blachowski et al., 2015). These results relied on two measurement epochs and did not allow to study temporal, as well as spatial (observations were confined to levelling lines) variations in more detail.

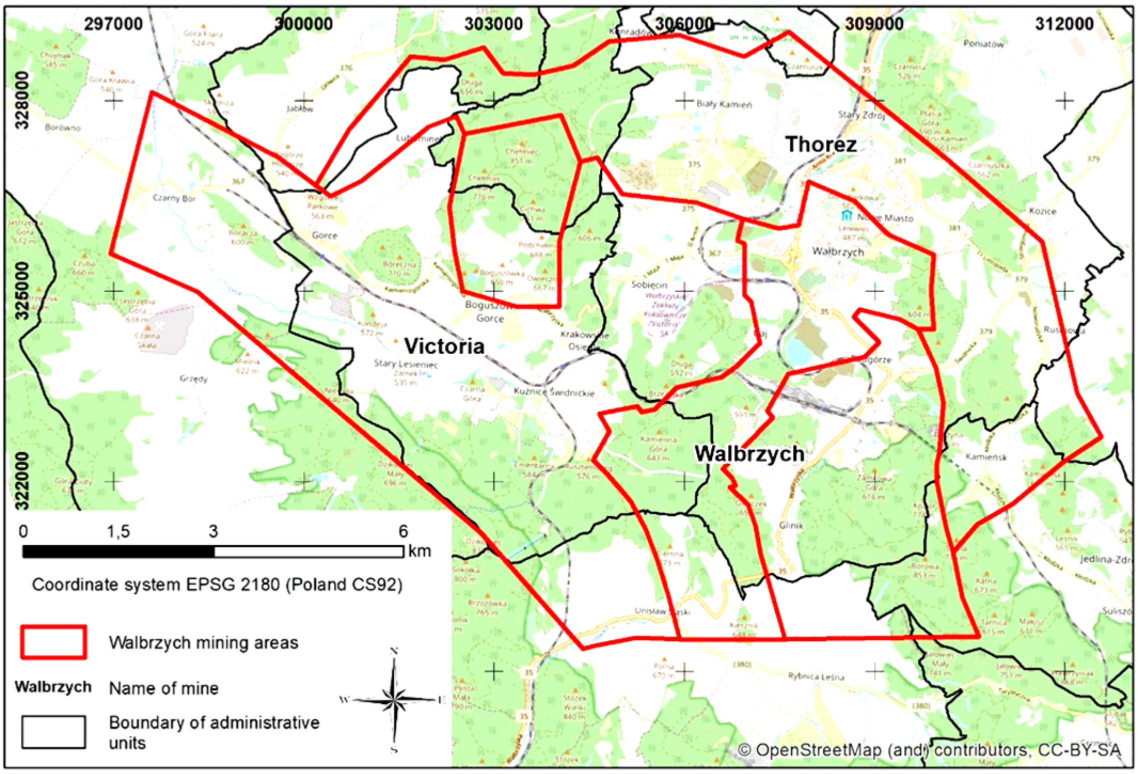

Fig. 3 Boundaries of mining sites of the Wałbrzych district.

MATERIALS AND METHODS

The characteristics of satellite radar interferometry, i.e.: frequency of SAR image acquisition, size of the area covered by observations, accuracy and ability to use historical data going back to early 1990's in case of ESA's satellites allow to determine and study ground displacements in line of sight (LOS) of SAR sensor with much greater flexibility than traditional surveying techniques that provide discrete data limited to location of levelling lines. In addition, results of levelling campaigns usually require interpolation to estimate deformation over large mining area and frequently data are unobtainable after closedown of mine.

In both cases, the Ostrava and Wałbrzych sites, the DORIS processing environment was used for formulation of interferograms (Kampes and Usai, 1999). Temporal analysis with PSInSAR technique was done based on StaMPS algorithms (Hooper et al., 2004). Details of the PSInSAR processing procedure has been described in (Hooper et al., 2004 and Hooper, 2006). The Wałbrzych study has been based on processing of 31 ERS-1/2 images from track 308 and 45 scenes from track 79. In the case of the Ostrava site, datasets of ERS-1/2 for track 494 and Envisat for track 415 satellites have been processed. Altogether 77 images were available, 49 from ERS-1/2 satellite (1995-2000 period) and 28 from Envisat satellite (2003-2010 period). For both, the Wałbrzych and Ostrava sites the ERS-1/2 orbits were descending and Envisat orbit was ascending. The master scenes selected for ERS-1/2 track 308 was 1998-01-06, for track 79 it was 1997-08-03 and for track 494 it was 1996-04-29. The Envisat data master scene was 2005-05-31. A list of satellite scenes, data capture time and master scene information for all the tracks used in processing has been given in attachment 1.

For the purpose of analysis and visualization of PSInSAR results, we have used hexagon tessellation and divided the area of abandoned mines into regular hexagons with segment length of 100 m. Regular hexagons are the closest shape to a circle that can be used for regular tessellation of a plane. The advantages of a hexagonal grid are: reduced edge effects, i.e. the lowest perimeter to area ratio of any regular tessellation of the plane, identical neighbours and identical distance between centroids for all neighbours. Using GIS spatial join function we have calculated statistics for particular cells based on their spatial congruency with PS points. The results have been presented and commented in the following part.

RESULTS

OSTRAVA SITE

Urban areas such as the Ostrava city are the most suitable targets for InSAR. The coherence is preserved high in most of the urbanized area. The phase stable pixels have an outstanding density. Because the rate of subsidence is relatively small in the post-mining time period, it is possible to reliably estimate the subsidence velocities by PSInSAR.

Datasets of both ERS-1/2 (1995-2000) – track 494 and Envisat (2003-2010) – track 415 satellites have been processed using PSInSAR implemented by

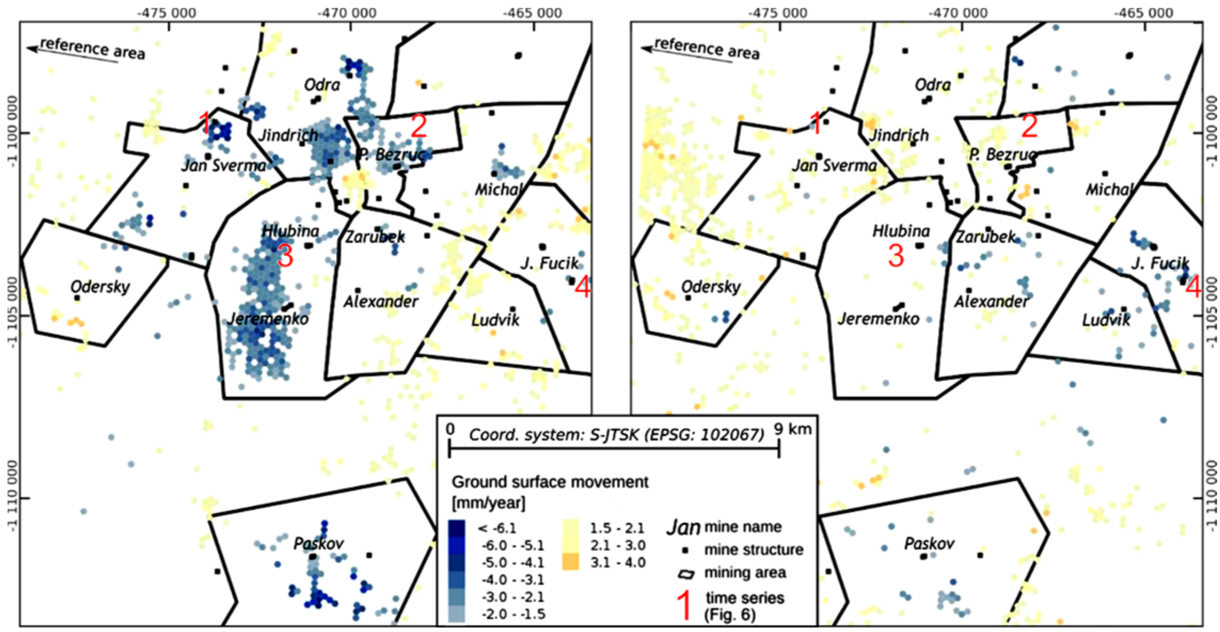

Fig. 4 Maps of average LOS displacements velocity based on PS processing of ERS-1/2 1995-2000 (left), and Envisat 2003-2010 (right) over the Ostrava site.

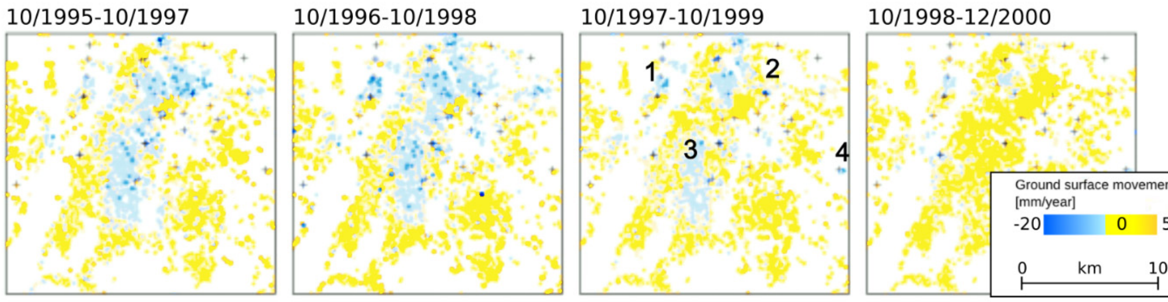

Fig. 5 Series of two-year average maps based on ERS-1/2 processing over the Ostrava site (numbers depict mine locations corresponding to plots in Figure 6).

StaMPS algorithms. From the 49 available ERS-1/2 images, only 26 were used for the processing (others were removed due to presence of strong decorrelation mainly due to either snow cover or strong atmospheric artefacts). In the case of Envisat, only 23 images were used from the 28 available images. Within the selected 15x10 km^2 area of Ostrava, 8500 PS-compatible pixels were identified (in average 57 PS/km^2) by ERS-1/2 processing while it was approx. 5600 pixels in the case of Envisat (i.e. 37 PS/km^2). For both cases, an area in Ostrava-Poruba has been used as a reference (stable areal of VSB-TU Ostrava).

Detected subsiding areas from processing of ERS-1/2 data fit well with locations of closed mines, as visible in Figure 4 showing the mean LOS velocity of the identified displacements (only for points showing temporal coherence higher than 0.75). For the case of Envisat, beginning with 2003 images, i.e. around a decade after the mine closures, such trend was not identified, the areas are mostly stable. Following Figure 5, it demonstrates the nonlinearity of the decay subsidence by plotting average mean velocity based on subselection of data series per two year period from the original ERS-1/2 dataset. Several local areas contain residual subsidence visible in both ERS-1/2 and Envisat datasets. This is demonstrated at Jan Šverma (number 1) and Julius Fučík (number 4) mines by plotting time series data of several PS points identified around them, in Figure 6. The Figure 6 also shows time series of estimated LOS displacements over Petr Bezruc (number 2) and Hlubina (number 3) mines where the subsidence is not identified within Envisat data. Note the dates of closure of the mines included in Figure 6.

According to ERS-based InSAR measurements, the Jan Šverma mine kept a decay subsidence during 8 years after the closure of mine activities that is in accordance with local knowledge for the Ostrava region. Data from Envisat show a slow continuing subsidence at this location. On the other hand, at the

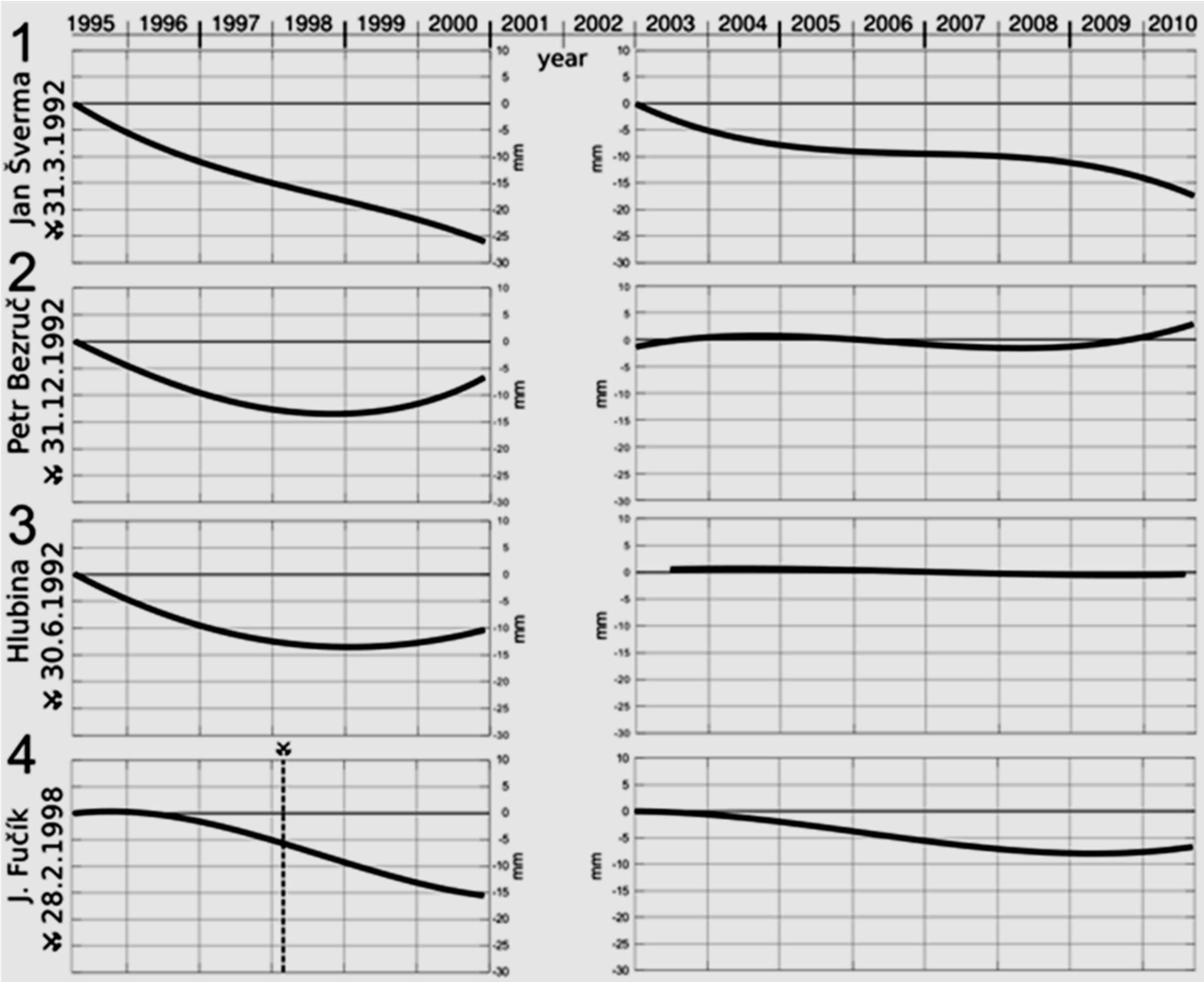

Fig. 6 Time-series of LOS displacements of PS points within a 150 m radius at selected locations at Jan Šverma (1), Petr Bezruč (2), Hlubina (3) and Julius Fučík (4) mines (see locations in Figure 4). Point measurements are being fit by a 3-degree polynomial. Dates below mine names depict dates of mine closures.

Petr Bezruč mine area, ERS-1/2 data show a change in the end of measurement series continuing to a shallow uplift in further time period. This effect can be possibly related to stress readjustment of the rock massif, as well as to changes of redisposition of underground water as seen in the case of Wałbrzych. Area around Hlubina mine got stabilized, Julius Fučík activity that stopped in 1998 caused a decay subsidence visible also in later Envisat data. For a deeper understanding, further investigations should take place.

WAŁBRZYCH SITE

For the 1995-2000 ERS-1/2 data, we have identified 10 398 PS points for two satellite tracks 79 (2 958 PS points) and 308 (7 440 PS points) located mainly in developed areas. Within the former mining grounds in average 24 PS/km^2 were identified for track 79 and 58 PS/km^2 were identified for track 308. The area beyond boundaries of former mining grounds was stable.

The maximum rates of uplift are 12 mm/year for track 79 and also 12 mm/year for track 308. The maximum rates of subsidence are -8 mm/year for both tracks. Thus, the maximum observed uplift amounted to 60 mm and the maximum subsidence to -40 mm. The map of ground surface movements in Line of Sight (LOS) represented as hexagon grid with 100 m segment length has been shown in Figure 7.

The Wałbrzych mines closed between 1994 and 1998, operation in Victoria and Wałbrzych mines stopped in 1994, and the Julia/Thorez one in September 1996. Small part of the Wałbrzych mine extracting anthracite functioned until 1998.

Subsidence continued in the boundaries of the Wałbrzych mine (marked with No. 1 and No. 2 in Figure 7), as well as in the NE part of the Victoria mine (location No. 3 in Figure 7) – presented with cold blue colours in Figure 7. These parts belong to the the Victoria-Chrobry water basin. According to measurements taken in mine shafts (Fiszer and Gogolewska, 2003), the groundwater table had been

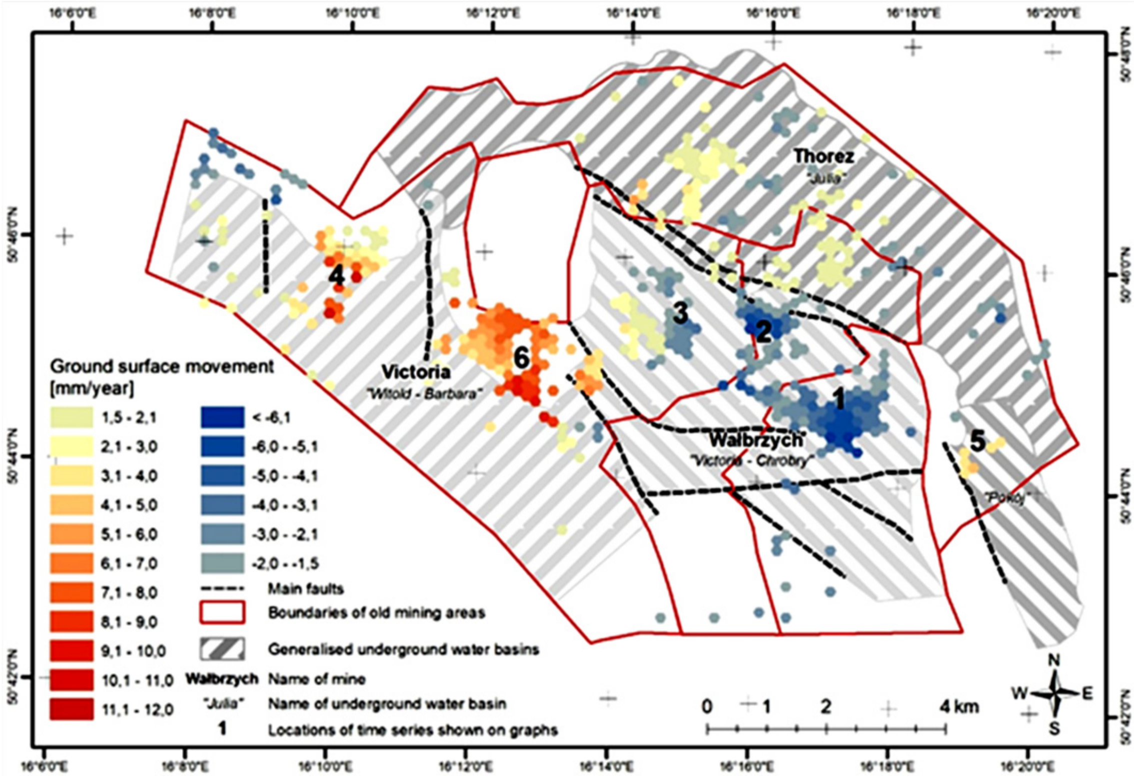

Fig. 7 Average movements (LOS) of ground surface between 1995-2000 in the Wałbrzych Coal Basin

kept there at -184 m a.s.l. as mining continued there until 1998. The groundwater table was then restored from 1998 to 2002 when it reached 400 m a.s.l. The dynamics of ground movements in the Wałbrzych mine and the NE part of the Victoria mine areas are shown in Figure 8. They indicate subsidence reaching -30 mm to -40 mm depending on particular site with location No. 3 manifesting the most consistent decaying subsidence trend.

We have identified areas of elevation in the boundaries of the *Victoria* mine – presented with warm colours (marked as No. 4 and No. 6 in Figure 7), as well as in the eastern part of the *Thorez* mine (marked as No. 5 in Figure 7). The values of the latter are very close to error of their estimation. The area of elevation in the western part of the abandoned *Victoria* mine correlates with the *Witold-Barbara* water basin where groundwater table rise between 1994 and 1999 from 210 m a.s.l. to 500 m a.s.l., as mine water drainage had been stopped there (Fiszer and Gogolewska, 2003). The area of elevation in the eastern part of abandoned *Thorez* mine correlates with the *Pokoj* water basin where the groundwater table has been restored to 430 m a.s.l. (rise of 210 m) between mid-1995 and mid-1997. Mining in these parts of Wałbrzych Coal Basin finished in 1994. The dynamics of ground surface movements for these parts are shown in Figure 9. They indicate consistent averaged elevation reaching up to 25 mm in these particular locations. The uplift can be attributed to increase in rock mass hydrostatic pressure as water filled voids left in the rock mass and redistribution of stresses.

DISCUSSION

Information on ground motion has been obtained from ERS-1/2 data processed with PSInSAR technique. For the Ostrava site Envisat, data has been used in addition. In case of the Wałbrzych site, datasets for two ERS-1/2 satellite tracks have been processed to determine average ground movements. The Ostrava study is based on data from one track. The same software solutions have been applied, DORIS and StaMPS for analysis of ground movements in the Ostrava and the Wałbrzych areas. Both studies have focused on urbanised areas of former mining sites and have been based on the PSInSAR processing methodology. Similar permanent scatterer (PS) point densities have been obtained for both sites for ERS-1/1 data used.

Mining in the analysed parts of the Ostrava and the Wałbrzych sites stopped at approximately the same time, i.e.: 1992 for the *Jan Šverma* mine, 1994 for the *Odra*, the *Victoria* and the *Wałbrzych* mines and 1996 for the *Thorez* mine. In both regions, cessation of mining was a gradual process. In the *Wałbrzych* region hydrogeological conditions have allowed for controlled rise of groundwater levels, separately for mines associated with different underground water basins. This was the reason for

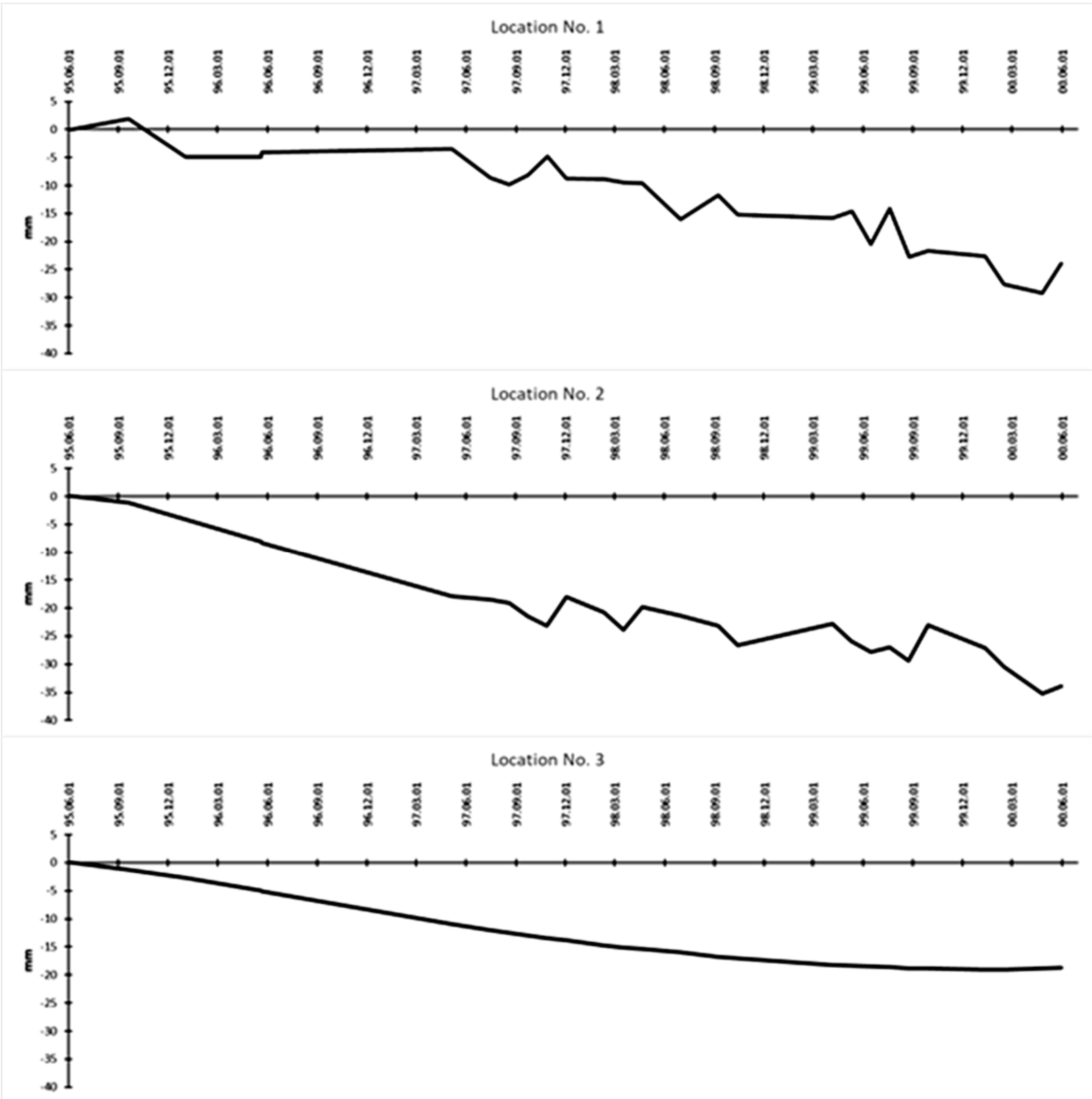

Fig. 8 Time-series of LOS displacements of PS points representing identified areas of subsidence within a 150 m radius at selected locations at Wałbrzych mines (see locations in Figure 7).

differentiated ground movements, subsidence in central parts of the mining fields where mining stopped completely in 1998 and uplift in external areas (towards W and NE) where restoration of underground water levels had happened earlier (between 1994 and 1998). In case of the Ostrava site, the entire area has experienced gradually decreasing subsidence, and in the case of the *Odra* mine, stabilization and gentle uplift in the second period (2003-2010) that was analysed with Envisat data. For the Wałbrzych site, results of a study described in Milczarek et al. (2017) for the 2002-2009 period, indicate uplift of up to 4 mm/year in the central part of the coal basin where subsidence occurred between 1995 and 2000. The other areas remained stable.

Maximum observed subsidence rates were similar for both coal basins and reached from -6 to -8 mm/year for the Ostrava and Wałbrzych sites respectively. The rate of elevation in the Wałbrzych site has been approx. 1.5 higher than the rate of subsidence. Significant elevation has been observed in the Ostrava site in the second period 2003-2010 in one part (*Jan Šverma* and *Julius Fučík* mines) and stabilization in the other (*Petr Bezruč* and *Hlubina* mines). These differences in the picture of ground movements between the compared coal basins can be attributed to dissimilarities in time of mine flooding as regulation of underground water levels has influence on distribution of pressure in rock massif. This can be the reason of identified deformations at the given mine area, as well as regional variances in geological and mining settings. Based on the results from both sites the following general trend for these coal mining sites can be identified: decreasing residual subsidence

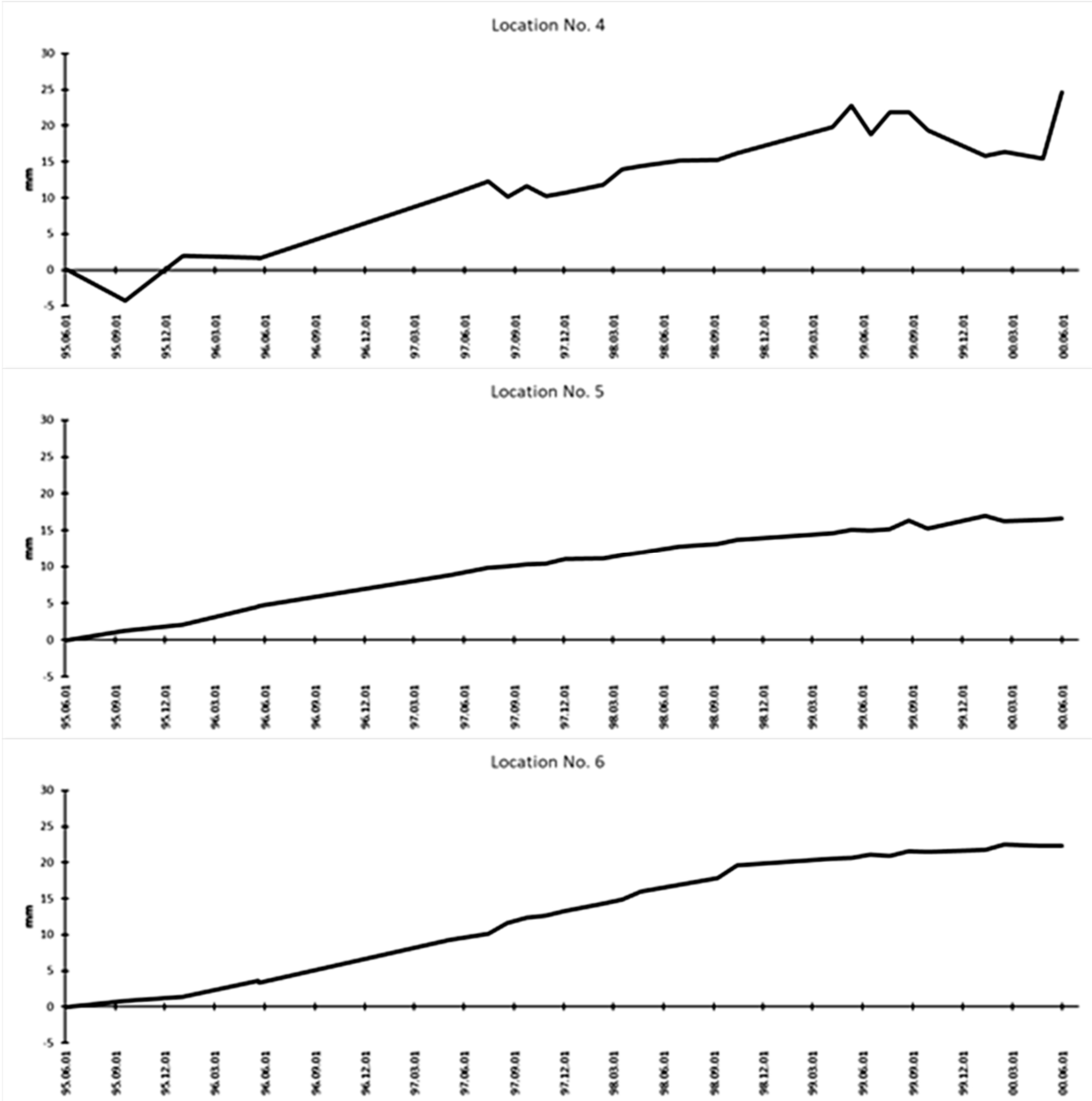

Fig. 9 Time-series of LOS displacements of PS points representing identified areas of elevation within a 150 m radius at selected locations at Wałbrzych mines (see locations in Figure 7).

after cessation of mining followed by gentle elevation and stabilisation (insignificant ground movements smaller than error of their estimation). Our findings are in accordance with the results of other studies of former coal mining sites pointing to the effect of stress redistribution in rock mass following cessation of water drainage. The presented differences, i.e. faster ground surface response (start of uplift after restoration of former groundwater level) in the Wałbrzych site than in the Ostrava site arise from local (geological and mining) differences between the analysed areas.

CONCLUSIONS

We have presented a comparative study of two former underground coal mining sites located in the Czech Republic and in Poland. Both areas have been closed in the mid 1990's of the 20th Century due to complicated geological and mining conditions and unfavourable economic circumstances. Knowledge from other former mining sites suggested that these sites may experience ground motions following the end of mining. As geodetic surveys by mine services have been stopped limiting access to data needed for analysis of present day condition of ground surface we have taken the advantage of satellite radar interferometry PSInSAR processing technique to obtain surface deformation information. We have observed residual subsidence in both areas of up to -8 mm/year, as well as elevation, which we correlated with zones where possible readjustment of rock mass stress has happened following restoration of underground water levels. Rate of elevation was greater for Wałbrzych site with value of up to +12 mm/year. The process of upward ground movement is more visible in the Wałbrzych site.

However, complete information on the process of secondary deformations in these areas requires longer time of observations and this is the target of further studies.

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REFERENCES

Abdikan, S., Arıkan, M., Sanli, F.B. and Cakir, Z.: 2014, Monitoring of coal mining subsidence in peri-urban area of Zonguldak city (NW Turkey) with persistent scatterer interferometry using ALOS-PALSAR. Environ. Earth Sci., 71, 9, 4081–4089. DOI: 10.1007/s12665-013-2793-1

Bateson, L., Cigna, F., Boon, D. and Sowter, A.: 2015, The application of the Intermittent SBAS (ISBAS) InSAR method to the South Wales Coalfield, UK. Int. J. Appl. Earth Obs. Geoinf., 34, 249–257. DOI: 10.1016/j.jag.2014.08.018

Blachowski, J., Milczarek, W. and Grzempowski, P.: 2015, Historical and present-day vertical movements on old mining terrains - case study of the Walbrzych Coal Basin (SW Poland). Acta Geodyn. Geomater., 12, 3 (179), 227–236. DOI: 10.13168/AGG.2015.0020

Černý, I. (ed.): 2003, Coal mining in Ostrava-Karvina district. Ostrava, Anagram, (in Czech).

Dopita, M. and Aust, J.: 1997, Geology of the Czech part of the Upper Silesian Basin. MZP, Praha, 278 pp, (in Czech with English summary).

Dopita, M. and Kumpera, O.: 1993, Geology of the Ostrava-Karviná coalfield, Upper Silesian Basin, Czech Republic, and its influence on mining. Int. J. Coal Geol., 23, 1-4, 291–321. DOI: 10.1016/0166-5162(93)90053-D

Chudek, M.: 2002, Geomechanics with elements of mining environment and ground surface protection. Wydawnictwo Politechniki Śląskiej, Gliwice, (in Polish).

Chwastek, J.: 1980, Mine surveying and protection of mining areas, Wrocław, (in Polish).

Caro-Cuenca, M., Hooper, A.J. and Hanssen, R.F.: 2013, Surface deformation induced by water influx in the abandoned coal mines in Limburg, the Netherlands observed by satellite radar interferometry. J. Appl. Geophys., 88, 1–11. DOI: 10.1016/j.jappgeo.2012.10.003

Fiszer, J. and Gogolewska, A.: 2003, Changes of groundwater conditions during the process of Lower Silesian Coal Basin closure. Wroclaw University of Technology, Institute of Mining Engineering Report, No. 35, (in Polish).

Gee, D., Bateson, L., Sowter, A., Grebby, S., Novellino, A., Cigna, F., Marsh, S., Banton, C. and Wyatt, L.: 2017, Ground motion in areas of abandoned mining: Application of the Intermittent SBAS (ISBAS) to the Northumberland and Durham Coalfield, UK. Geosci., 7, 3, 85. DOI: 10.3390/geosciences7030085

Hooper, A., Zebker, H., Segall, P. and Kampes, B.: 2004, New method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scattrers. Geophys. Res. Lett., 31, L23611. DOI: 10.1029/2004GL021737

Hooper, A.: 2006, Persistent scatterer radar interferometry for crustal deformation studies and modeling of volcanic deformation. Ph.D. Thesis, Stanford University.

Jiránková, E. and Lazecký, M.: 2016, Specifics in the formation of subsidence troughs in the Karvina part of the Ostrava-Karvina Coal District with the use of radar interferometry. Acta Geodyn. Geomater., 13, 3(183), 263–269. DOI: 10.13168/AGG.2016.0008

Kampes, B. and Usai, S.: 1999, Doris: The Delft object-oriented Radar Interferometric Software. In: Proceedings ITC 2nd ORS Symposium, August 1999.

Kominowski, K.: 2000, Geology and hydrogeology. In: Kowalski, A. (Ed.), Mining and surface protection. Experiences from the Walbrzych mines, Central Mining Institute, Katowice, 33–48, (in Polish).

Mei, S., Poncos, V., and Froese, C.: 2007, InSAR mapping of millimetre-scale ground deformation over Frank Slide, Turtle Mountain, Alberta. Alberta Energy and Utilities Board, EUB/AGS Earth Science Report, 1–62.

Majer, J., Matějček, J., Matušek, Z. et al.: 1985, Coal Mining in Czechoslovakia. Profil Ostrava, 800 pp, (in Czech).

Milczarek, W., Blachowski, J. and Grzempowski, P.: 2017, Application of PSInSAR for assessment of surface deformations in post-mining area – case study of the former Walbrzych hard coal basin (SW Poland). Acta Geodyn. Geomater., 14, 1(185), 41–52. DOI: 10.13168/AGG.2016.0026

Raucoules, D., Colesanti, C. and Carnec, C.: 2007, Use of SAR interferometry for detecting and assessing ground subsidence. C. R. Geosci., 339, 5, 289–302. DOI: 10.1016/j.crte.2007.02.002

Rapantová, N. and Grmela, A.: 2004, Hydraulic modelling of liquidated partial coal basins flooding in Ostrava-Karviná coal district. Podzemná voda, 10, 1, 82–93, *(*in Czech with English summary*)*.

Samsonov, S., d’Oreye, N. and Smets, B.: 2013, Ground deformation associated with post-mining activity at the French–German border revealed by novel InSAR time series method. Int. J. Appl. Earth Obs. Geoinf., 23, 142–154. DOI: 10.1016/j.jag.2012.12.008

Wójcik, J.: 2008, Surface change due to mining in the Walbrzych area. Landf. Anal., 9, 339–342, (in Polish with English summary).

Attachment 1. List of ERS satellite scenes available for the study. Master scenes are marked in bold.

No.	ERS-1/2 track 308 Wałbrzych	ERS-1/2 track 79 Wałbrzych	ERS-1/2 track 494 Ostrava	Envisat track 415 Ostrava
1.	1995-05-01	1995-04-15	1995-04-09	2003-01-07
2.	1995-06-05	1995-05-20	1995-10-01	2003-02-11
3.	1995-07-11	1995-06-24	1996-02-18	2003-08-05
4.	1995-09-19	1995-06-25	1996-04-29	2003-10-14
5.	1996-01-02	1995-07-29	1996-09-16	2004-03-02
6.	1996-05-20	1995-07-30	1997-02-03	2004-05-11
7.	1996-05-21	1995-09-03	1997-03-10	2004-06-15
8.	1997-05-06	1996-05-04	1997-04-14	2004-07-20
9.	1997-07-15	1996-05-05	1997-09-01	2004-11-02
10.	1997-08-19	1996-06-08	1998-02-23	2005-04-26
11.	1997-09-23	1996-06-09	**1998-03-30 - master**	**2005-05-31 - master**
12.	1997-10-28	1996-07-13	1998-05-04	2006-06-20
13.	1997-12-02	1996-07-14	1998-09-21	2006-07-25
14.	**1998-01-06 master**	1996-08-18	1998-10-26	2007-02-20
15.	1998-02-10	1996-09-22	1999-02-08	2007-05-01
16.	1998-03-17	1996-10-27	1999-03-15	2007-09-18
17.	1998-04-21	1997-01-05	1999-04-19	2008-03-11
18.	1998-06-30	1997-04-20	1999-05-24	2008-04-15
19.	1998-09-08	1997-05-25	1999-09-06	2008-07-29
20.	1998-10-13	**1997-08-03 master**	1999-10-11	2009-02-24
21.	1999-03-02	1997-09-07	2000-02-28	2009-05-05
22.	1999-04-06	1997-10-12	2000-04-03	2010-08-03
23.	1999-05-11	1997-11-16	2000-05-08	2010-09-07
24.	1999-06-15	1997-12-21	2000-09-25	
25.	1999-07-20	1998-01-25	2000-10-30	
26.	1999-08-24	1998-03-01	2000-12-04	
27.	1999-09-28	1998-04-05		
28.	2000-01-11	1998-05-10		
29.	2000-02-15	1998-07-19		
30.	2000-04-25	1998-08-23		
31.	2000-05-30	1998-09-27		
32.	-	1998-11-01		
33.	-	1998-12-06		
34.	-	1999-03-21		
35.	-	1999-04-25		
36.	-	1999-05-30		
37.	-	1999-07-04		
38.	-	1999-08-08		
39.	-	1999-09-12		
40.	-	1999-10-17		
41.	-	1999-11-21		
42.	-	1999-12-26		
43.	-	2000-04-09		
44.	-	2000-05-14		
45.	-	2000-06-18		