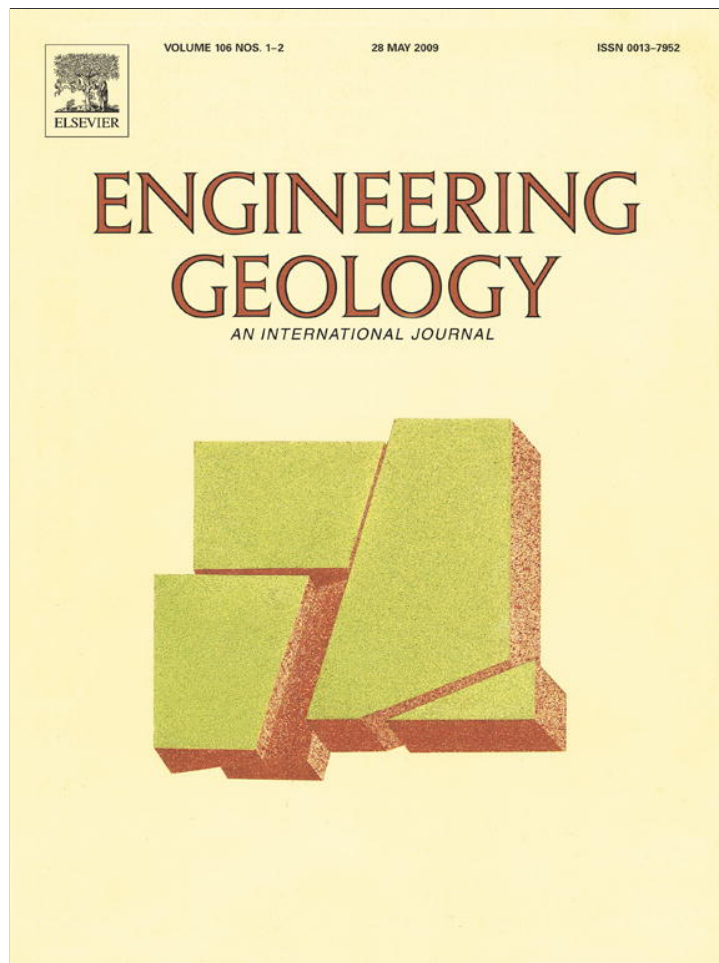


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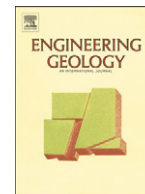
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InSAR analyses of terrain deformation near the Wieliczka Salt Mine, Poland

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ABSTRACT

European Remote Sensing satellites ERS-1 and ERS-2 synthetic aperture radar (SAR) data are used to analyze terrain deformation in the area of Wieliczka, Poland using interferometric techniques. Terrain deformations in Wieliczka are due to (i) salt mining, (ii) catastrophic suffusion caused by water inflows to the mine and (iii) landslides in the southern part of the region. To discriminate between different deformation regimes differential SAR Interferometry (D-InSAR) and persistent scatterers interferometry (PSI) are used. A comparison with published information based on leveling data is performed. It can be concluded that rapid subsidence caused by catastrophic water inflow cannot be identified with InSAR techniques. However, both D-InSAR and PSI retrieve information about slow subsidence due to mine convergence. These data match with subsidence maps constructed from leveling data. A limited amount of coherent scatterers were identified on landslides. Some scatterers can be related to buildings with clear damage caused by landslide movement.

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1. Introduction

More than 2000 underground chambers have been excavated in the Wieliczka Salt Mine (Fig. 1) during the last 700 years. The slow convergence of these cavities has induced several meters of subsidence. Apart from slow convergence, the mine suffers from catastrophic events such as collapse and water inflow, causing sinkholes and rapidly developing localized subsidence (e.g. up to 1.5 m during 6 months in 1992). Additional geohazards in the Wieliczka region are landslides, as it is located at the edge of the Carpathian Mountains. Up to now, no clear relation between mining subsidence and the triggering of landslide movement has been found.

One of the biggest advantages of InSAR techniques is its ability to study the past by exploring data archives. In this study we evaluate different InSAR techniques (conventional and persistent scatterers interferometry (PSI)) to detect and monitor various types of terrain deformations in the Wieliczka region. For validation purposes published data of terrestrial leveling provided by the mining company are explored. The study is performed based on archived ERS-1/2 data and evaluates whether is possible to detect and identify terrain deformations due to subsidence following from convergence and landslides. Additionally, the interferograms are checked for the presence of rapid surface deformations caused by a catastrophic water inflow in 1992.

2. Geologic context

The saliferous formation extends as a narrow strip along the edge of the Carpathians, from the city of Wieliczka in the west to the city of Bochnia in the east. According to Garlicki and Wilk (1993) the salt complex of the Miocene salts consists of two structures in the flysch sediments. The lower structure of layered salt is strongly tectonically displaced with fallen flexures. The overlying complex of megabreccia consists of salty clays with large salt blocks. The described salt deposits and the flysch sediments are forming an overthrust. North from that structure the Tertiary water-bearing rocks, the Chodenice beds, are situated. They consist mainly of clays, weakly cemented sandstones and conglomerates, probably strongly fractured during the tectonic events, which folded the Miocene complexes (Figs. 1 and 2). The Chodenice beds are the main source of hydrogeological hazard for the mine (Zuber et al., 2000).

The salt mine covers a 7 km long, 900 m wide and 300 m deep area. The mining activity has created about 2000 chambers with a total volume of about $7.5 \times 10^6 \text{ m}^3$ and over 190 km of galleries at nine levels and several local mid-levels spreading between –50 and –290 m below the terrain surface. The old non-operational part of the mine (135 m below ground level) is used as a tourist attraction and a museum since 1965. Because of its historical uniqueness and geological attractiveness, UNESCO has entered the Wieliczka Salt Mine into the List of the World Cultural and Natural Heritage in 1978 (Wójcik and Mrozek, 2002).

3. Terrain deformations at Wieliczka

Two types of subsidence are associated with salt mining in Wieliczka. First, there is slow, nearly linear subsidence due to

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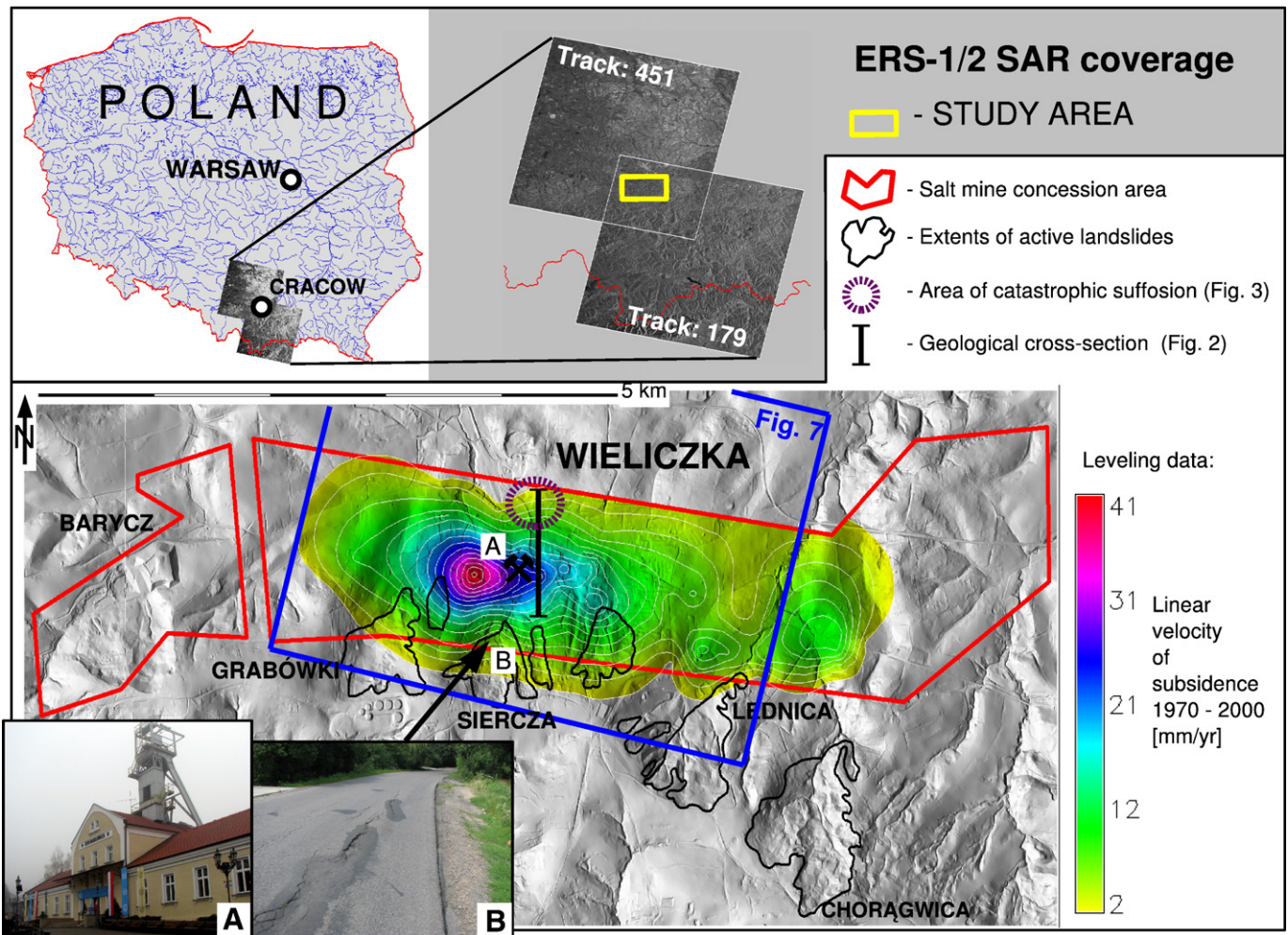


Fig. 1. Location of the study area with the extents of applied SAR scenes. Land subsidence data based on leveling campaigns from 1970 to 2000 after (Szewczyk and Kortas, 2004).

convergence of galleries and chambers. The second type is fast, non-linear subsidence due to catastrophes like suffusion caused by ground-water inflows into the mine and/or mine chamber collapses. During seven centuries of exploitation many catastrophic intrusions of water and loose sands were caused by the lack of knowledge on the boundary of the deposit and the character of adjacent rocks (Zuber et al., 2000). The first significant signs of ground subsidence (0.1–0.3 m), in particular close to Barycz in the West, were observed between 1926 and 1934. After World War II the landscape featured numerous depressions and ponds, up to 27 m deep. In 1974 the largest salt chamber collapsed. Due to the degradation of the natural landscape, a part of the former mining area has been used as a municipal dumping site for Cracow. Moreover, salt exploitation and mining practices have caused salination of soils and deterioration of water conditions (Wójcik and Mrozek, 2002).

Conventional geodetic measurements of subsidence in Wieliczka are acquired since 1925 when the first measurement network was established (Kortas, 2007). Recent measurements focused on the monitoring the long-term subsidence due to slow convergence of salt caverns. Fig. 1 shows two subsidence sub-bowls occurring between 1970 and 2000. The largest bowl is located near the Kościuszko shaft and shows a total amount of subsidence of 1085 mm (Szewczyk and Kortas, 2004). This corresponds with a linear velocity of 36 mm/year. However, the subsidence does not always have a constant rate, in fact, it is decreasing since 1980. According to Kortas (2007) the maximum subsidence velocity was measured in 1962 (72 mm/yr) and now decreased to 22 mm/yr. The second, smaller sub-bowl is located 3 km east from the main bowl and the subsidence here is related with

convergence of caverns in the eastern part of the mine (Szewczyk and Kortas, 2004). At that location the subsidence velocities are more linear, reaching 14 mm/yr. The observed decrease of the subsidence rate in the main bowl was analyzed against the total volume of exploited caverns. The highest volume of all caverns of $6.5 \times 10^6 \text{ m}^3$ is reached in the 1980s and since that time it is constantly decreasing. Some caverns were backfilled with sands, while the volume of the others is decreasing by the convergence. Since the 1980s the salt exploitation has decreased and finally it ceased in 1992 (Kortas, 2007).

Nonlinear subsidence is commonly associated with collapses caused by catastrophic water inflows into the mine. One of the most catastrophic inflows started in April 1992 in the Mina Gallery, see Figs. 2 and 3. Problems started during the reconstruction of the Mina gallery which was created before the First World War and stopped 20 m beyond the salt deposit in the gypsum and clay cover. The catastrophe began on the night of 13 April 1992 when the flow rate increased to 200–300 l min^{-1} , i.e., nearly equal to the sum of the other water inflows at that time (Garlicki and Wilk, 1993). As a consequence, washing out (suffusion) took place (Garlicki et al., 1996) and consequently the concentration of suspended matter in the inflow water increased rapidly to $\sim 500 \text{ kg m}^{-3}$ (Zuber et al., 2000). Subsidence started to develop almost immediately after the catastrophic increase in water inflow had been recorded in Mina gallery, see Fig. 3. From April 1992 to November 1992 subsidence reached 1500 mm and to October 1994 it was 2274 mm (Garlicki and Wilk, 1993). Since 1996 the subsidence decreases to nearly 20 mm/yr and the measurements taken in August 1999 show the total value of 2335 mm (Wojnar and Bieniasz, 2000). The size of the area

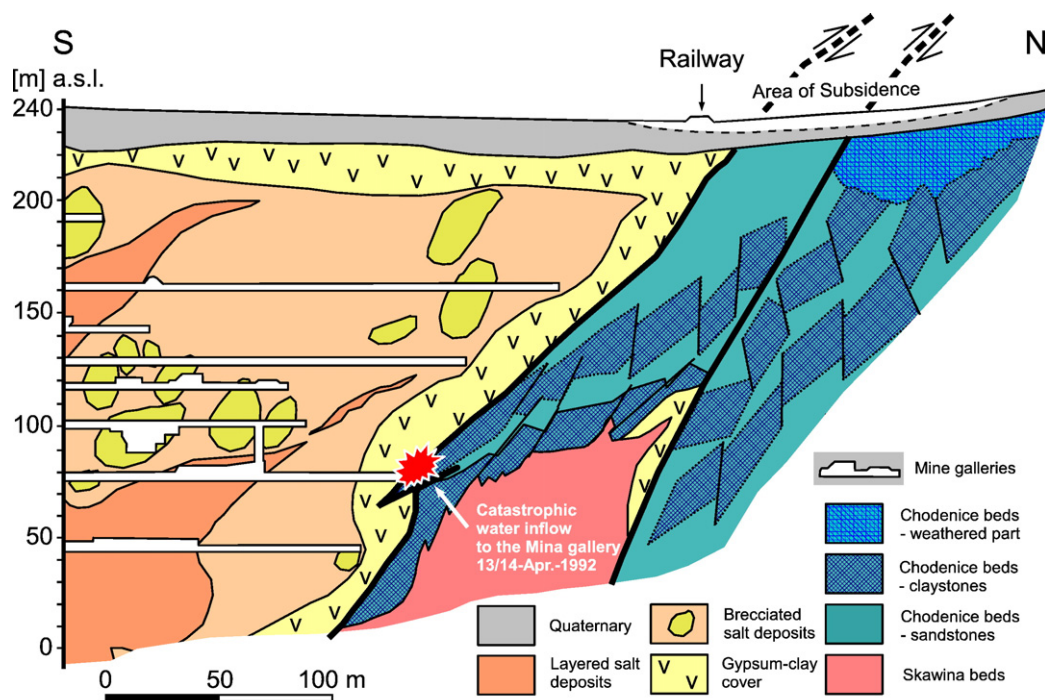


Fig. 2. Geological cross-section in the vicinity of the Mina gallery showing the situation after catastrophic water inflow in 1992. After Garlicki and Wilk (1993); Garlicki et al. (1996).

affected by subsidence is relatively small ($\sim 300 \times 300$ m) in November 1992 (Garlicki and Wilk, 1993) and $500 \text{ m} \times 500 \text{ m}$ in October 1994 (Wojnar and Bieniasz, 2000).

3.1. Landslides

The location at the margin of the Carpathians—in the zone where the Carpathians are thrust over the Miocene deposits of the Carpathian Foredeep—covers three structural zones consisting of rock series with different ages. First the Carpathian Flysch rocks with differentiated lithology and complicated tectonics. Secondly there are tectonically disturbed claystones and Miocene sands. The third zone covers the overlying youngest Quaternary deposits, mainly loess and colluvial loams. Such configuration and specific arrangement of the rock series is dominant for landslide development, many of which are recently active. The large landslides are associated with the zone of the trust-fault where flysch rocks are laying over the Miocene deposits.

Wójcik and Mrozek (2002) found five large landslides to the south of Wieliczka in the region of Lednica, Grabowki and Choragwica hamlets (Fig. 1). Here, large fragments of the slopes are occupied by landslides covering the total area of 2 km^2 . The landslide zone begins with 23 m high niches close to Choragwica hill. The activity of the landslides manifests in various parts of the colluvia causing damages to buildings and infrastructure. In the vicinity of Siercza and Grabowki landslides have damaged the roads in 3 places. According to Varnes (1978) the described landslides could be classified as the compound landslides type. The upper parts of these landslides are permanently active and because of that a section of the road surface has been subsiding by 5 cm. Landslide velocities are varying from a few mm/yr to 20 cm/yr. The lower parts of landslides are most active. Slide surfaces (shear surfaces) occur commonly at depths of 3–4.5 m which was confirmed by observations in tectonic windows.

4. Terrain deformation measurements with SAR interferometric techniques

SAR Interferometry (InSAR) is a technique for extracting information related to the topography of the Earth's surface (Goldstein et al.,

1988). It uses the phase difference between the radar echoes from repeated SAR (Synthetic Aperture Radar) observations of the same area. The result of this operation is known as an interferogram, presenting relative phase differences 'wrapped' within 2π radians. By applying phase unwrapping techniques (Ghiglia and Pritt, 1998) it is possible to reconstruct the full unambiguous signal. First interferometric studies, focused on topography retrieval, demonstrated the applicability of InSAR to digital elevation model generation (Ferretti et al., 1997). Differential InSAR (D-InSAR) represents a branch of InSAR that exploits the temporal baseline between consequent SAR acquisitions to derive phase differences which correspond with terrain displacements. D-InSAR has already been successfully used in different applications: the monitoring of volcanic activity, earthquakes, glacier dynamics, landslides and urban subsidence. In many cases D-InSAR has demonstrated its capability in measuring surface movements of the order of centimeters. A good overview of D-InSAR technique and its applications was given by Bamler and Hartl (1998); Massonnet and Feigl (1998); Rosen et al. (2000) and Hanssen (2001).

The main problem associated with D-InSAR is the so-called temporal decorrelation, due to changes in the electromagnetic properties and/or relative positions of scatterers within a resolution cell. Moreover, D-InSAR is very sensitive to atmospheric signal delay. The variable water vapor distribution related to the turbulent character of the atmosphere creates an interferometric phase contribution (Hanssen et al., 2006). For singular interferograms, this atmospheric phase screen (APS) is impossible to remove and therefore the accuracy of measuring small deformations is significantly reduced. Due to those properties the operational use of D-InSAR is limited to a) short temporal baselines b) phenomena with strong deformation gradient in respect to radar wavelength within the acquisitions, c) areas with limited vegetation, and d) advantageous weather conditions during master and slave acquisitions. Subject to these limitations, many successful studies have been performed regarding subsidence due to underground mining (Perski and Jura, 1999; Wright and Stow, 1999; Raucoules et al., 2003). Fewer studies focused on landslides due to slow movement in the presence of vegetation (Colesanti et al., 2003; Hilley et al., 2004).

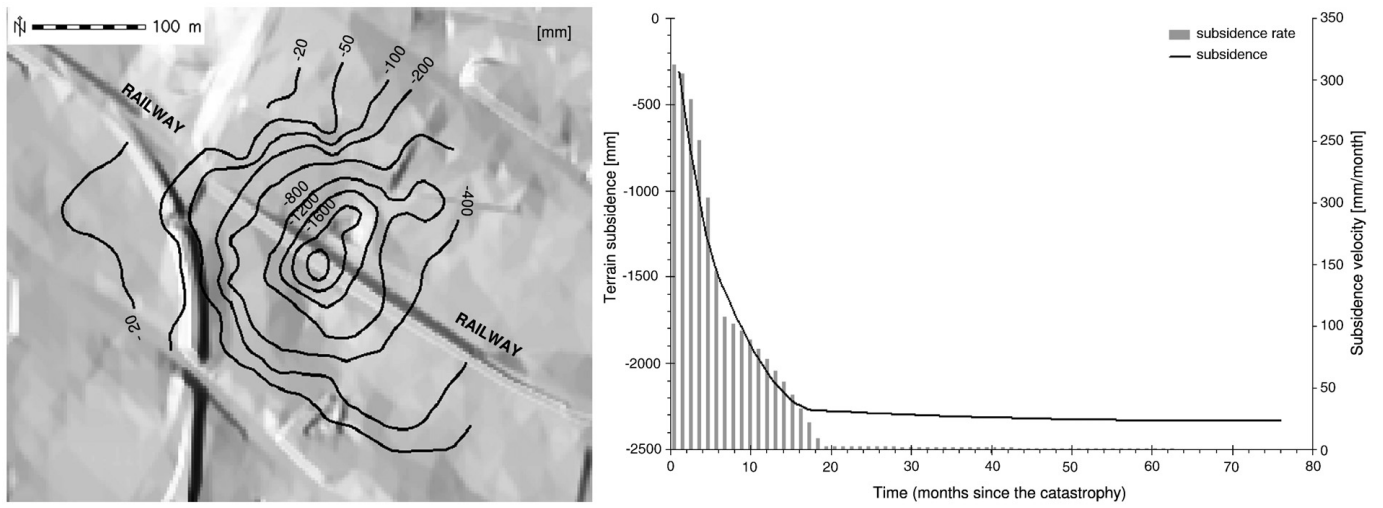


Fig. 3. The development of rapid subsidence caused by catastrophic inflow in April 1992. The contour map presents the situation in October 1992 (Wojnar and Bieniasz, 2000). The plot presents the temporal development of the center of subsidence bowl. The plot has been constructed based on data from publications of Garlicki and Wilk (1993); Wojnar and Bieniasz (2000); Szcwzyk and Kortas (2004); Kortas (2007).

To bypass the limitations mentioned above point wise InSAR techniques have been developed since 2000, see e.g. Ferretti et al. (2001). The initial method developed by POLIMI used radar point targets as 'natural' corner reflectors. The phase of such targets (labeled Persistent Scatterers, or PS) is not sensitive to small incidence angle variations and temporal decorrelation. The time series of interferometric phase is decomposed into (linear) deformation, topography (relative height) and APS. Such operation can only be performed for scatterers with coherent phase behavior over time. Fundamental in these point wise methods is the exploration of all available SAR images (typically more than 20 acquisitions) by coregistering and resampling them to the same master. Then the interferograms between all slave images and the master are computed. An overview of PSI applications for landslide studies has been given by Colesanti and Wasowski (2006). Other techniques, such as the Small Baseline Subset technique (SBAS) (Berardino et al., 2002) utilize several master images to construct an optimal set of interferograms with the smallest temporal and perpendicular baselines. The crucial element in the point wise analysis is the identification of potentially coherent points. The first selection might be based on amplitude dispersion as in the original PSI algorithm (Ferretti et al., 2001) or coherence as in case of SBAS or StaMPS (Hooper et al., 2004). Redundant observations are consecutively used to estimate the APS and the (linear) deformation. This estimation is based on the properties of the specific signals: APS is strongly correlated in space but not in time whereas deformation is usually strongly correlated in time (Colesanti et al., 2003).

It should be noted that the InSAR technique is capable only to measure path differences in its Line of Sight (LoS) direction. Therefore, having only the projection of three-dimensional displacement to the radar LoS, it is not possible to retrieve the full displacement vector. To properly decompose the displacement into horizontal and vertical components the InSAR measurements taken from two directions (ascending and descending interferograms) should be combined. For the third component, assumptions or the measurements taken by other techniques are necessary. Unfortunately within this study only data acquired from single direction (descending satellite pass) were available. In case of mining subsidence we assumed mainly vertical deformation therefore the vertical component from InSAR data was derived. In a case of landslides the only LoS deformation is considered since no ground truth data are available.

The main uncertainties associated with PSInSAR method are related to the proper phase unwrapping. In most cases the phase unwrapping errors are associated with low density networks of PS candidates and too long arcs. For non-linear deformations the phase component associated with the deformation signal might be mixed with atmospheric component. Therefore, the results of PSInSAR must be very carefully analyzed.

5. InSAR data analysis and interpretation

To study terrain deformations in Wieliczka both D-InSAR and PSI techniques were applied. D-InSAR was used mainly in an attempt to identify rapid subsidence associated with catastrophic water inflow in April 1992. Individual interferograms were also generated for long temporal baselines as a cross validation with PSI. Initially, the PSI analysis has been conducted as a "blind experiment," i.e., without prior knowledge of the expected deformation. When the first results had been obtained, PSI was used to study long-term subsidence due to convergence. Both D-InSAR and PSI methods were used to study deformations associated with landslides.

The interferometric processing was performed based on ERS-1/2 SAR images covering almost 7.5 years, from 18 June 1992 to 17 December 2000. Data acquired from two satellite tracks (Fig. 1) were used: 10 images from track 451 and 51 images from track 179. Only data from track 179 were used for PSI analysis whereas for D-InSAR processing both datasets were used. For PSI processing the TU Delft

implementation (Leijen et al., 2005) for Persistent Scatterers analysis was used. For D-InSAR processing, the Delft Object Oriented Interferometric Software (Doris) was used (Kampes et al., 2003). Doris was also used for interferogram generation during PSI processing. The main difference between the processing of those two datasets was in multilooking and filtering. In case of D-InSAR analysis the azimuth and range spectral filtering were applied. Since the original resolution of the SAR images is different in azimuth (lines) and range (columns) the data must be multilooked. During this step the interferograms were multilooked by 5 in azimuth direction (i.e. each 5 lines of the image were averaged into one). PSInSAR analysis requires that the phase of the pixel should be preserved. Thus the interferograms were not filtered and not multilooked. To improve the location of the PS points the SAR images were oversampled by factor 2 prior to interferogram generation.

Final analysis of the PSI results requires a GIS environment which allows combining all interferometric results and external data into a common reference system. For this purpose open-source GRASS (Geographic Resources Analysis Support System) was applied (GRASS-Development-Team, 2006).

To introduce interferometric data to GIS system the interferograms and PS points must be geocoded. To convert the data from slant-range geometry into cartographic coordinate system the acquisition timing, its geometry and terrain topography must be known. To support information about topography the DEM (Digital Terrain Model) must be used. For Wieliczka area the photogrammetric DEM of 1 m resolution was used. That type of DEM is a product available together with digital aerial orthophotomap provided by the regional (provincial) cartographic office in Krakow. The applied DEM allows precisely geocode standard interferograms (up to 0.5 pixels). In case of precise location of PS its proper geolocation depends whether the point is located on the terrain at the top of the building. Since the DEM represents the terrain surface (buildings and other structure were filtered out). It may introduce few meters error in a case of typical building height of 10 m.

5.1. PSI: analysis of time series of SAR observations

In the PSI processing 51 interferograms were used. After obtaining the first results the processing was repeated with a modified setup to ensure that the reference point to which all the observations are referred is not located within an area likely to be affected by deformation. For extraction of subsidence signals from SAR observations various models may be used (Leijen and Hanssen, 2007). However the application of a specific model should be tuned to a priori knowledge about the subsidence development in space and time. As terrestrial geodetic measurements since the 1980s proved that the deformation is steady-state (Kortas, 2007), a constant velocity model is applied. To improve the separation of that part of the interferometric signal related to topography the interferograms were regenerated and subtraction of topography with an external DEM was performed. As external DEM (Digital Elevation Model) the one-arcsecond DTED (Digital Terrain Elevation Data) of level-2 (Defence-Mapping-Agency, 1986) was used. The requirement of topography removal comes from the fact that Wieliczka is located in the Carpathians, in hilly terrain of 200 m topography (Fig. 1).

A large number (30,000) of PS points is detected within the study area of 18×18 km (average density of 92 PS/km²). Within the mine concession area (164 PS/km²) and surroundings (Fig. 4) 1895 PS points are detected. Most of the scatterers are related to buildings and are located within the densely urbanized center of Wieliczka, where the maximum PS density was 480 PS/km². Wieliczka is surrounded by villages and hamlets characterized by sparse urbanization which allow to get a good spatial distribution of scatterers (~30 points/km²) for the rest of the area of interest. Most of the scatterers are related there to buildings but also to other metallic and concrete objects like

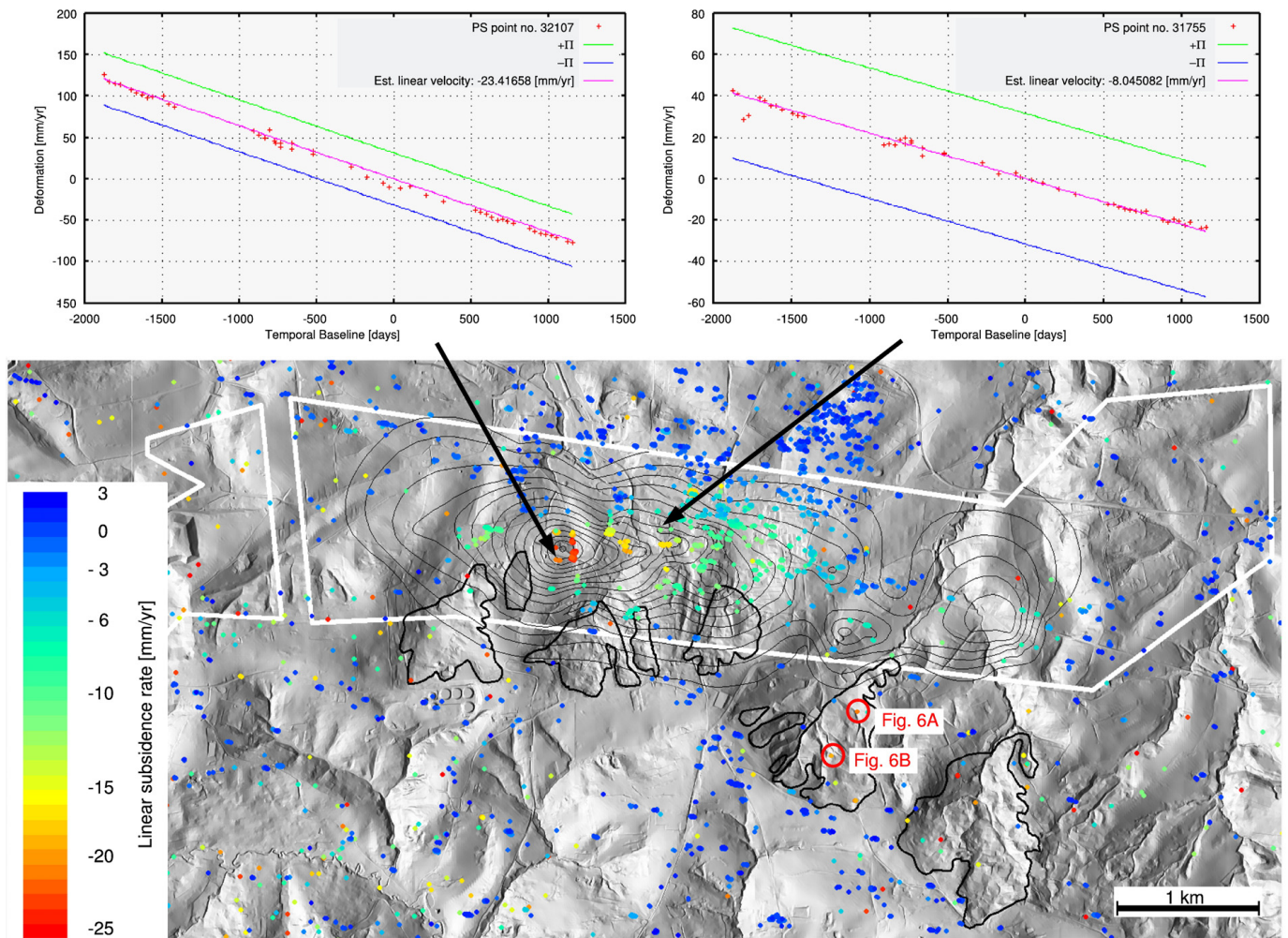


Fig. 4. Map of PS points in the Wieliczka region. The PS used as the reference point is located outside of presented crop.

fences, roads, and poles. General knowledge of the scatterer characteristics is obtained by comparison of PS locations with detailed topographic maps followed by field inspection.

The main subsidence bowl is detected but the low density of points does not allow restoring the full shape of secondary bowls in the eastern part. However, some points with velocities of about -6 mm/yr were detected in that region (Fig. 4). The eastern part of the subsidence area is more sparsely urbanized. The PSI data are compared with published subsidence maps constructed based on long-term leveling data (Szewczyk and Kortas, 2004; Kortas, 2007). Unfortunately the available data covers a different time period (1970–2000) which makes it impossible to draw precise quantitative conclusions about the quality of the InSAR measurements. Nevertheless, the main features of the subsidence bowls correspond very well in both leveling and PSI results (Fig. 4). The subsidence isolines are interpolated followed by the computation of the average linear velocity over 30 years. It can be noted that these velocities do not take the decrease of velocities that happened after 1980 into account. According to (Kortas, 2007) the decrease of subsidence rates measured on benchmarks is about 12%. Taking this value into account and

considering the difference between vertical and slant-range geometries both subsidence velocity data are compared (Fig. 5). For most PS the leveling linear velocities are 2 mm/yr higher than measured with PSI, while for some points the discrepancy can be up to 20 mm/yr. Assuming a very rough estimation of subsidence velocities from leveling data the obtained difference is considered to be very small. Similar study over Wieliczka PSI dataset has been recently performed independently by scientists from Bari Technical University and Italian Research Council (Wasowski et al., 2007). This group uses different implementation of PSI approach but the obtained preliminary results are very similar.

Some PS with different behavior, i.e., variable velocities have been found on the areas of known active landslides. The PS velocities are highly dispersed over the area: up to 25 mm/yr between neighbor points. Due to small number of man-made structures the PS density is very low that results in the weaker network and then in higher errors. In our study only points of overall very high coherence which locations correspond with the extent of the active landslides (Fig. 4) were considered. To verify the reliability of these points the field examination was performed. The coordinates of the points were plotted on the

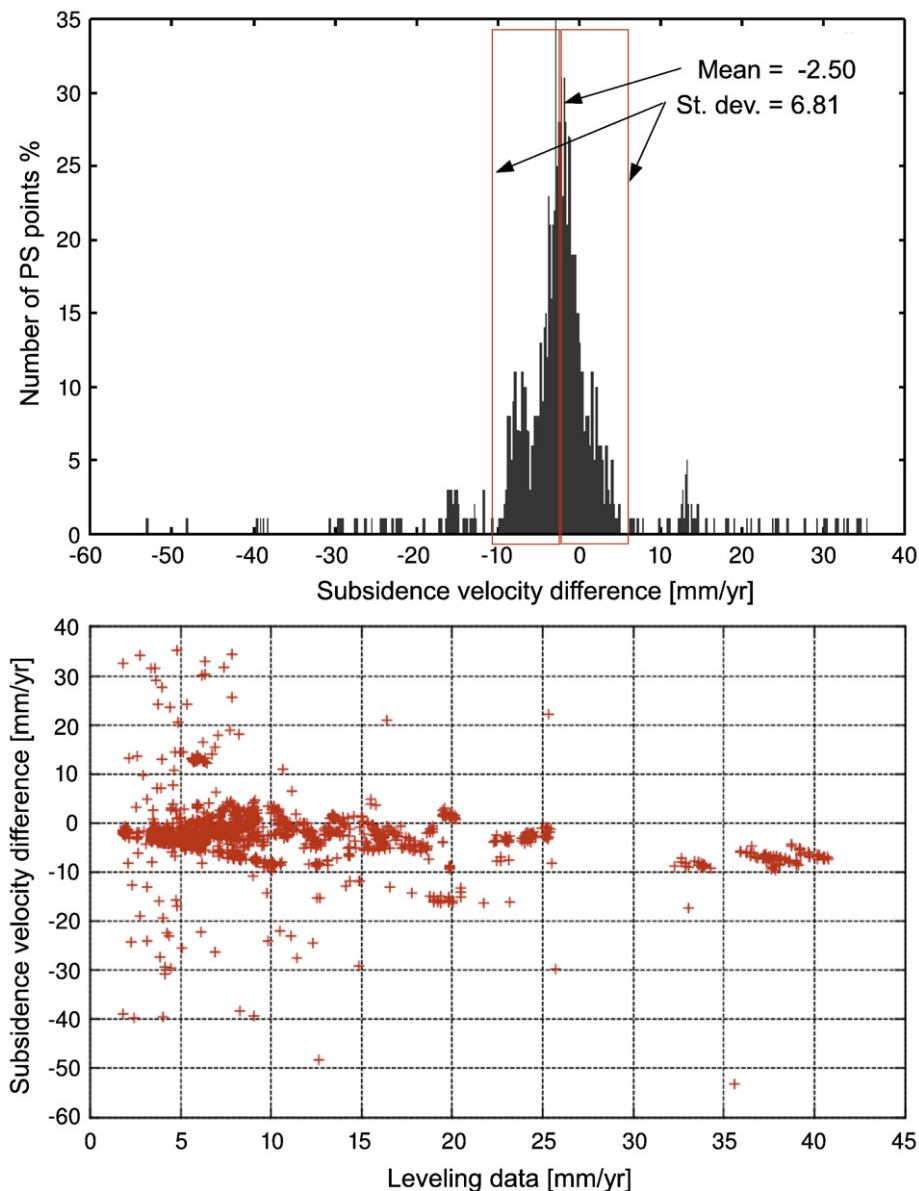


Fig. 5. Histogram of the difference between subsidence velocity values derived from the contour map (Szewczyk and Kortas, 2004) and PSI data. The scatter plot below shows the subsidence velocity difference against the deformations derived from leveling data. The high dispersion of the velocity differences could be noted for the points of very low deformations i.e. at the edges of subsidence bowls.

topographic map and loaded into field GPS receiver. During the field investigation some PS located on buildings with visible damage were identified, see Fig. 6. Unfortunately, a large number of PS was not identified and might relate to scattering from poles, power lines, fences, and roads, without clear evidence of damage. The field verification was focused mainly on the points with coherence higher than 0.8 and PS on landslides were verified in the field against the evidence of visible damage. During that work some buildings where construction damage and failures are visible have been identified (Fig. 6). For those located on the lowest part of the slopes the origin of the damage is not clear since these parts are also within the range of the influence of the mining-induced subsidence. However it should be noticed that many buildings located on the upper parts of the slopes have been damaged. The origin of the damage is not always clear since all failures are cracks, which are quickly repaired. Some of them may be caused by construction mistakes or bad quality building material.

As the northward direction of landslide movement (horizontal component) is not suitable for interferometry with polar satellite orbits (Colesanti and Wasowski, 2006), the observed movement is not spatially uniform. Each point behaves individually according to its local conditions and local movement direction. It should be also emphasized that PS velocity was calculated against linear model of deformation. Thus analyzed cases present the cases close to linear movements of relatively low magnitude (up to 25 mm/yr) that allow to preserve interferometric coherence and high backscatter amplitude over the time. Unfortunately our observations cannot be verified by

any quantitative measurement because the landslide movement is not measured there systematically.

5.2. D-InSAR: short baseline interferograms

A number of short temporal/perpendicular baseline interferograms is computed in order to detect surface deformation caused by catastrophic suffusion in 1992. All short baseline combinations of SAR images acquired between 1992 and 1993 are evaluated. Unfortunately due to decorrelation the deformation signal cannot be identified. The same procedure is then followed for images acquired after 1995. Some pairs represent tandems of ERS-1 and ERS-2 images acquired with a one day temporal span. Unfortunately, at that time the subsidence rate was already too small to be detected within a one day interval (Fig. 3), while pairs with a temporal baseline larger than 35 days were usually decorrelated. Retrieval of the signal of interest from the area affected by catastrophic subsidence was mainly hampered by volume scattering of due to vegetation. Apart from the railway that is crossing this area there are no other man-made structures in the vicinity. For data acquired in 1992 and 1993 the reason for decorrelation might also be the high subsidence rate at that time, resulting in an aliased signal due to the 2π limitation of InSAR (Meade and Sandwell, 1996; Hanssen, 2001; Baran et al., 2005). The only image pair in which a (rather noisy) fringe pattern related to suffusion is identified was acquired on 1 October and 10 December 1992. That period corresponds to very rapid development of the subsidence bowl of about 100 mm. However due

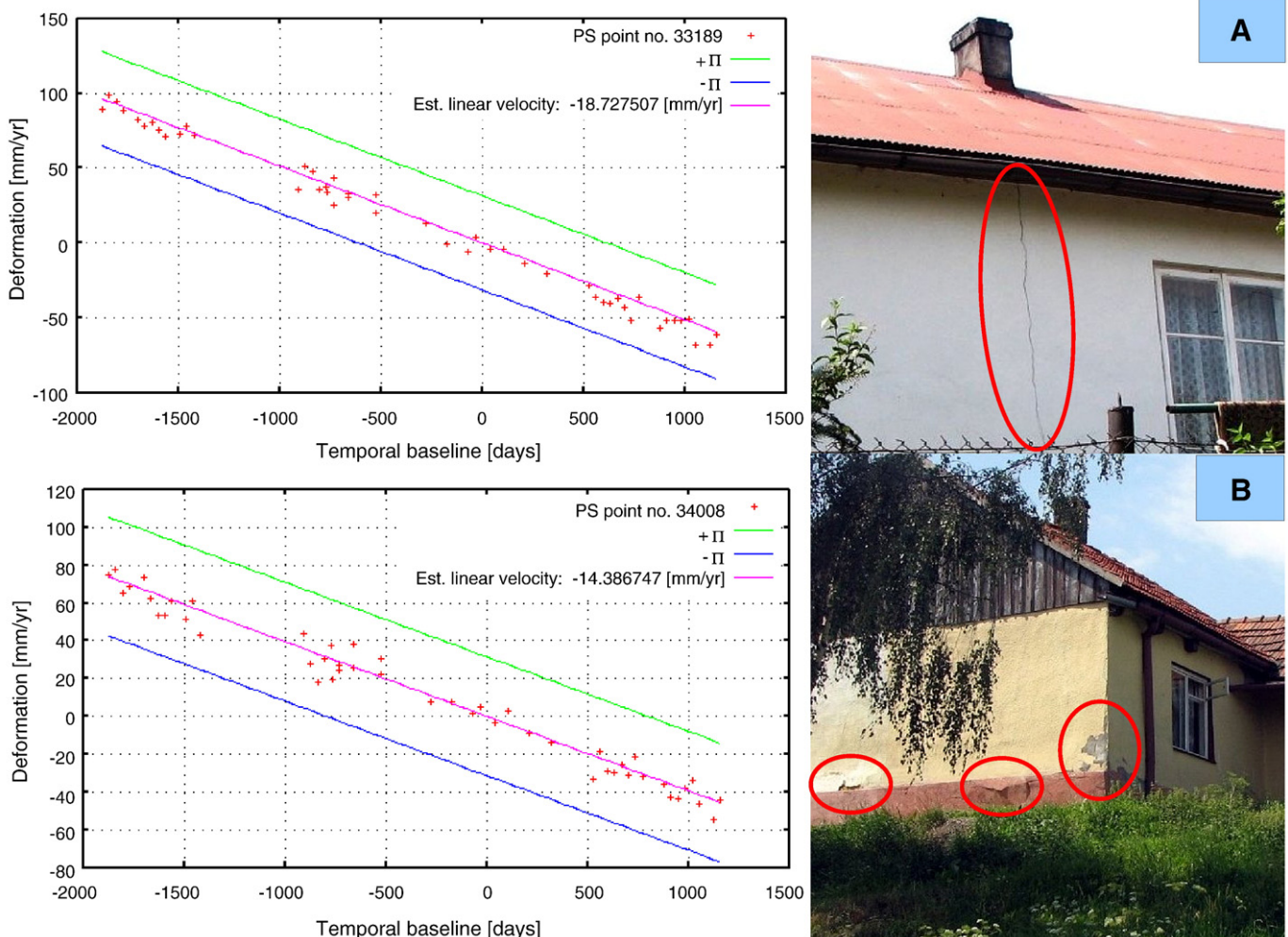


Fig. 6. Identification of PS points on landslides and visible evidence of construction damage caused by the landslide. Presented time series of corresponding deformation show linear behavior. It could be noted that the roofs remain undamaged that probably allows preserving phase of backscattered SAR signal over the time.

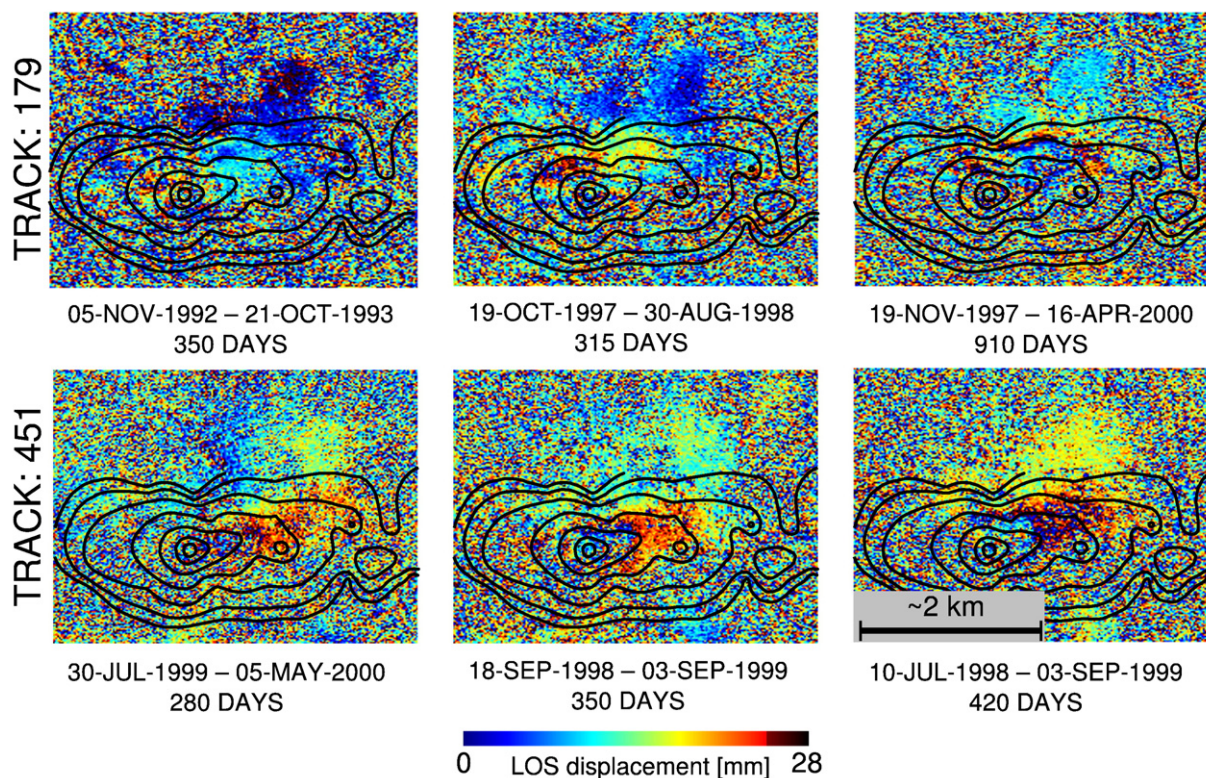


Fig. 7. Long temporal baseline interferograms with visible fringe pattern of long-term salt mining subsidence. To improve the signal-to-noise ratio all interferograms are filtered with a modified Goldstein filter (Baran et al., 2003). To increase interpretability of the interferograms the simplified contours of subsidence as from Fig. 1 were plotted.

to the very low coherence it is impossible to draw any conclusions about the subsidence values but the shape of the pattern corresponds well with the contour map by (Wojnar and Bieniasz, 2000).

The long-term subsidence due to convergence is identified by only a few coherent interferograms with small geometrical but long temporal baselines see Fig. 7. The main subsidence bowl is partially visible mainly in the urbanized region of Wieliczka. The noisy interferometric fringes allow interpreting the general subsidence rate of 30 mm/yr but due to low coherence it is difficult to trace details of their spatial pattern. The same fringe pattern is observed in interferograms from other master/slave combinations for both satellite tracks. This confirms that the observed signal is not of atmospheric origin. In the interferograms from 18-Sep-1998 to 03-Sep-1999 and 19-Oct-1997 to 30-Aug-1998 the secondary subsidence sub-bowl can be recognized, see Fig. 7.

6. Conclusions

SAR interferometric analysis of Wieliczka, Poland is performed. Because of the occurrence of (i) landslides, (ii) slow subsidence, and (iii) rapid mining subsidence different InSAR techniques are applied. It is found that the rapid subsidence caused by catastrophic water inflow into the mine cannot be detected with SAR interferometry because (a) the subsidence area was very small (500×500 m) and (b) the subsidence velocity in the initial stage was very high and therefore such signal is very difficult to detect using C-band SAR with the resolution of 4×20 m. Moreover, (c) there is a lack of SAR acquisitions in the period 1993 – 1995 when subsidence rates of a few cm/month would be detectable by C-band SAR, and (d) there is decorrelation of the signal due to vegetation.

Slow subsidence due to convergence of mine caverns has been detected in individual D-InSAR interferograms and with PSI. Some coherent long temporal baseline interferograms allow the identification of the main and secondary subsidence bowls. Due to the low coherence no quantitative data can be derived from these interfero-

grams. The same subsidence pattern was observed in the PSI data. The comparison of PSI subsidence velocities with those derived from leveling data show high correlation (correlation coefficient 0.78).

Some PS are detected in areas of active landslides. The PS data show very variable deformation values but it should be noticed that the general direction of the landslides is not optimal for InSAR analysis. In case of landslides on the northern slopes of Choragwica hills the landslide direction is almost orthogonal to the range direction in which the ERS SAR system is most sensitive. Nevertheless, during field inspection some persistent scatterers were identified on buildings with visible damage caused by landslide movement. To improve and verify the results ERS data acquired from opposite direction i.e. from the ascending orbits should be used. Unfortunately, the ascending set for that area contains only 11 scenes and therefore is not suitable for PSIInSAR.

This study shows that the combination of various InSAR techniques may help to interpret and decompose terrain deformation signal of various origins. Archived ERS-1/2 SAR data shows again its extraordinary potential to reconstruct the deformation signal in the past which is not possible with any other existing measurement technique.

Because of its historical uniqueness and geological attractiveness the Wieliczka Salt Mine was placed on the List of World Cultural and Nature Heritage by UNESCO in 1978 (Wójcik and Mrozek, 2002). Unfortunately the salt exploitation and mining practices have also caused some negative environmental effects like subsidence and dangerous water inflows. The importance of protection of historical mine galleries makes the application of new terrain deformation techniques extremely valuable.

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