

SATELLITE INTERFEROMETRY REVEALS SPATIAL PATTERNS OF SUBSIDENCE IN THE ANCIENT WIELICZKA SALT MINE (UNESCO HERITAGE SITE, POLAND)

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ABSTRACT

We present the first Persistent Scatterers SAR Interferometry (PSI) data on the subsidence phenomena in the town of Wieliczka. The town is home to a unique salt mine, over 700 years old, one of the best known tourist attractions in Poland. Each year the mine is visited by about 1 million tourists from all over the world and in 1978 UNESCO placed it on its first International List of the World Cultural and Natural Heritage. There is evidence that the mining legacy has influenced the ground and building stability in the town, which is sited directly above the mine. The application of the PSI SPINUA technique has led to the identification of numerous radar targets (over 100 PS/km²), suitable for ground motion monitoring in the Wieliczka area. The results show the presence of continuous subsidence with average movements ranging from about 1 to 2 cm/yr in the period 1992-2000. The detected subsiding zone corresponds well to the extent of the underground salt mine. There are also indications of possible linkages between the mine-induced subsidence and the presence of the relatively large landslides occurring on the north slopes facing the Wieliczka area.

Key words: Persistent Scatterers Interferometry; mining-induced subsidence; landslides.

1. INTRODUCTION

This work presents the first SAR interferometry data on the spatial distribution and amount of subsidence in the Wieliczka area. The town of Wieliczka is home to a unique, over 700 years old salt mine, one of the best known tourist attractions in Poland. Each year the mine is visited by about 1 million tourists from all over the world and in 1978 UNESCO placed it on its first International List of the World Cultural and Natural Heritage (<http://www.kopalnia.pl>). Since the Middle Ages over 7.5 million m³ of underground passages have been excavated, extending from level I (64 m below the ground surface) to level IX (at 327 m depth). This includes over

2000 chambers, 200 km of galleries and numerous shafts. The salt deposit has been exploited under an area extending 6-7 km in E-W direction and about 1 km wide. There is evidence that the mining legacy has had a negative influence on the ground and building stability in the town, which is sited directly above the mine. One of the latest damaging events occurred in the early 1990's, following a large increase in groundwater inflow to the northern part of the mine. It produced a few meters of localised subsidence and associated landslide phenomena that interrupted the railway and damaged the 17th century Franciscan Monastery. Furthermore, today many buildings in the town show clear signs of distress and ground stability is an important issue. The Wieliczka area is also one of the test sites selected for the ALOS ADEN 3595 project, whose general goal is to foster an integrated approach (EO and in situ data) to pre-disaster detection and monitoring of landslides, subsidence and related ground instability hazards. In the last several years differential SAR interferometry has become a useful tool for detecting and long-term monitoring of terrain motion (e.g. [1]). In this context Wieliczka is of particular interest, because it is affected by both mining-induced subsidence and landslide phenomena. It thus offers an opportunity of investigating possible linkages between mine subsidence and slope instability.

2. PHYSICAL SETTING

Wieliczka is a small town (about 20,000 inhabitants) located in southern Poland, about 14 km SE of the city of Cracow (Fig. 1). Apart from the town centre, the surrounding areas are characterised by a low degree of urbanisation and predominantly agricultural land use. The town falls within a minor E-W trending depression (240 to 270 m a.s.l.), bordered to the south by low lying (elevations within 400 m a.s.l.), gently sloping hills of the northernmost portion of the Carpathian Mountains. Despite modest elevations, the hillslopes facing Wieliczka are prone to landsliding. The presence of the north-verging Carpathian thrust zone confers considerable complexity to the local geological set-

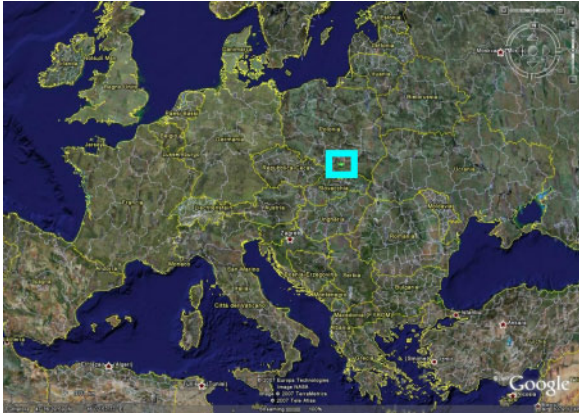


Figure 1. Location map of the study area (Wieliczka site) in southern Poland.

ting. The salt rock deposit is found within the tectonically disturbed, Miocene age units that include marly clays, mudstones and sandstones [2]. These units are mantled in the Wieliczka depression by Quaternary sediments (mainly clays, sands, gravel) and colluvial/eluvial materials, whereas the Jurassic-Cretaceous age limestones and flysch formations form the bedrock.

3. DATASET AND PSI PROCESSING

The selected dataset consists of 39 ERS-1/2 descending acquisitions (track 179, frame 2601) and covers a period from 1992 to 2000. Before selecting the radar images we examined historical precipitation records of the Wieliczka meteorological station. This was done to avoid ordering images acquired on days with significant snow cover or heavy snow/rain precipitations. The SAR data were analyzed using the SPINUA (Stable Point Interferometry over Unurbanised Areas) algorithm (see [3] for more details), which belongs to the family of Persistent Scatterers Interferometry (PSI) processing tools [5]. In particular, within SPINUA, a step-wise approach can be used for co-registration of multitemporal imagery [4]. Furthermore, a patch-wise processing scheme is adopted that relies on processing small zones (usually a few km²) within a larger area of interest. The patches are selected with the aim to optimise the density and the distribution of potential PS. Their small size allows to use locally linear approximations of the atmospheric phase signal, which in turn ensures high processing robustness. Atmospheric phase residuals can then be interpolated over larger areas through a kriging procedure. Final data consist of a precisely georeferenced PS database, including several pieces of information such as point average velocity, DEM estimated error, as well as the complete displacement time series measured at the acquisition dates. The data can be imported into several geographic visualization environments such as Google Earth.

Differential interferograms of the Wieliczka test site were generated by using an external SRTM-derived DEM with

spatial resolution of 90×90 m².

4. RESULTS OF PSI ANALYSIS AND INTERPRETATION

4.1. Wide-area overview

The initial PSI analysis included also the city of Cracow, situated about 14 km NW of the Wieliczka test site (Fig. 2). This resulted in the identification of numerous PS within the city area. Most of them are motionless and thus indicate the general stability of Cracow and its surroundings. The patch-wise approach produced very good results also in the case of Wieliczka. In particular, several thousands of PS were obtained on the town and the neighbouring area (Fig. 2), with average density amounting to about 100 PS/km². Furthermore, the Line of Sight (LOS) velocities of the PS immediately pointed out that the Wieliczka site is characterised by a significant number of downward moving radar targets, extending approximately in E-W direction.

4.2. PS in Wieliczka

To facilitate the interpretation of the PSI results we superimposed the geo-coded PS distribution on a high-resolution QuickBird image of the Wieliczka area (Fig. 3). A simple visual examination of the image revealed that a majority of radar targets is concentrated in the town centre, whereas rural areas show a very limited number of PS. The PS coincide mainly with buildings and industrial infrastructures and locally appear to be aligned along the roads. Significantly, the entire town area, as well as the neighbouring areas to the west and east are consistently characterised by negative (downward) displacements. The moving PS indicate that a zone of marked subsidence extends for at least 4.5 km in roughly E-W direction. Nevertheless, the average LOS velocities show significant spatial variations, with maximum downward movements reaching 24 mm/yr in the western periphery of the town. Significantly lower velocities are present to the east of the Wieliczka centre (generally below 10 mm/yr). It is possible that the spatial variations in the subsidence rates in the Wieliczka area are linked to the past and recent salt mine history. To examine this possibility, in the following we focus on four smaller areas that have been and are still directly affected by the mine activity. In particular, starting from the western outskirts of the town we consider first the area of maximum subsidence. It is of interest to note that this area (Fig. 4-1) includes the two deepest mine shafts, Kosciuszko and Kinga, reaching, respectively 300 and 296 m below the ground surface. The PS velocities in the vicinity of Kosciuszko and Kinga shafts range, respectively, from -19 to -24 mm/yr and from -15 to -19 mm/yr. The second area of interest is centered around the Danilowicz shaft (Fig. 4-2). This is the third deepest shaft

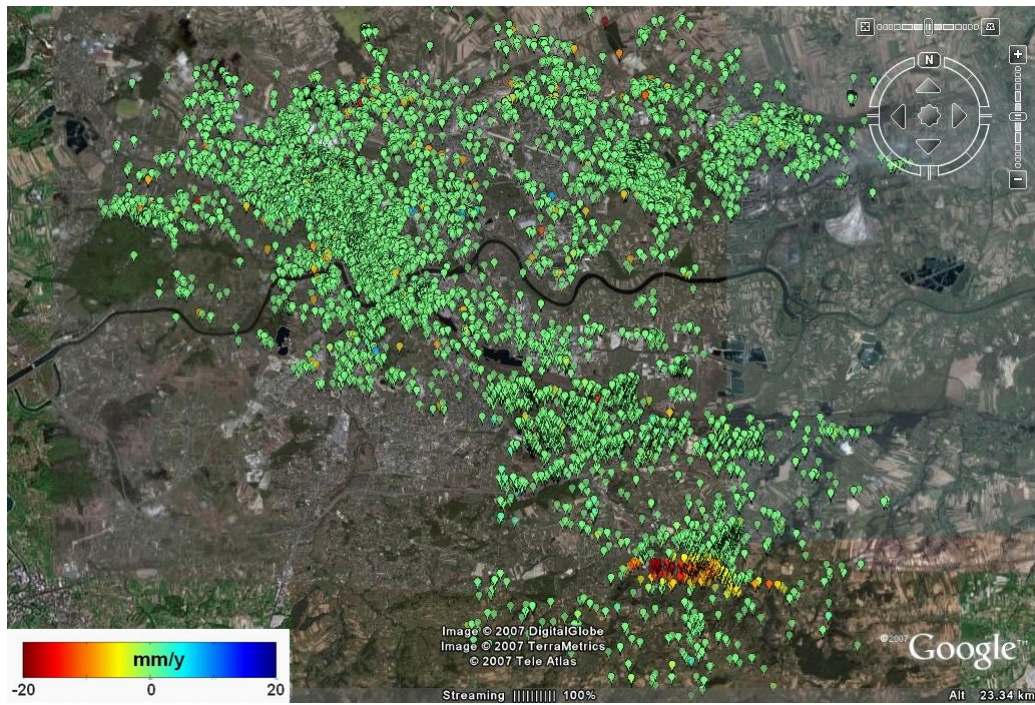


Figure 2. Geo-coded Persistent Scatterers (PS) distribution in the Cracow-Wieliczka area. Background optical image is from Google Earth. The average Line of Sight (LOS) velocity (for the period 1992-2000) has been saturated at ± 5 mm/yr for visualisation purposes. Note the predominance of motionless PS in the city of Cracow (upper part of the figure) and the presence of downward moving PS in the town of Wieliczka. The yellow rectangle indicates the area shown in Fig. 3.

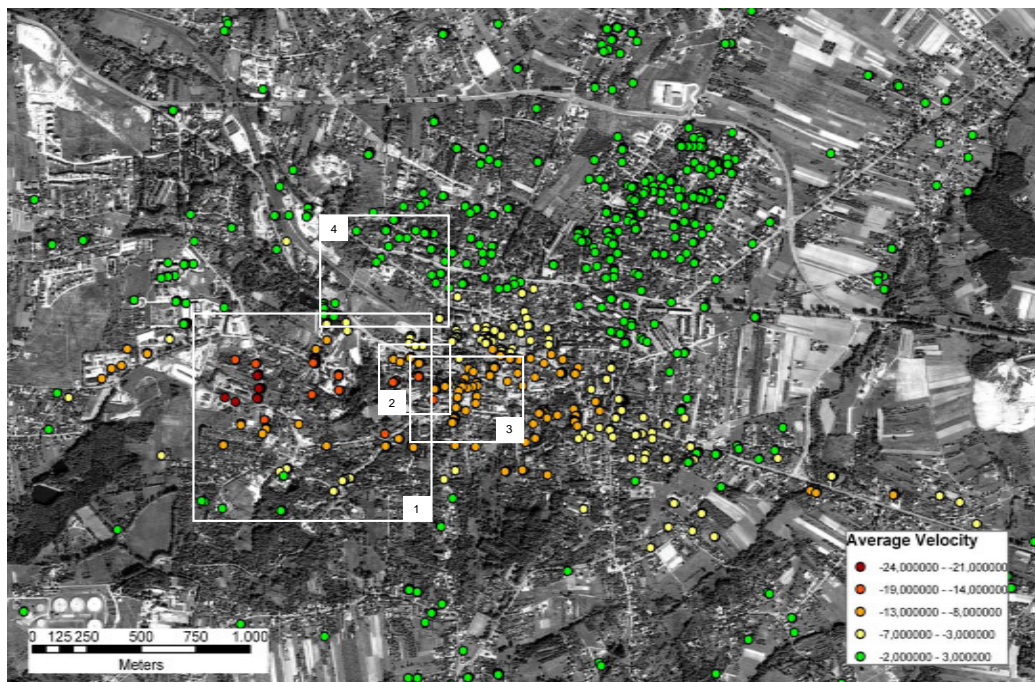


Figure 3. Geo-coded PS distribution superimposed on a high-resolution QuickBird image of the Wieliczka area. Note spatial variation in the average LOS velocities, with the highest displacement rates present in the area just west of the town centre (up to 24 mm/yr in the period 1992-2000). The numbered white rectangles mark 4 local areas of interest linked to the mining activity and shown in Fig. 4. Rectangle 3 covers the central part of the town of Wieliczka.

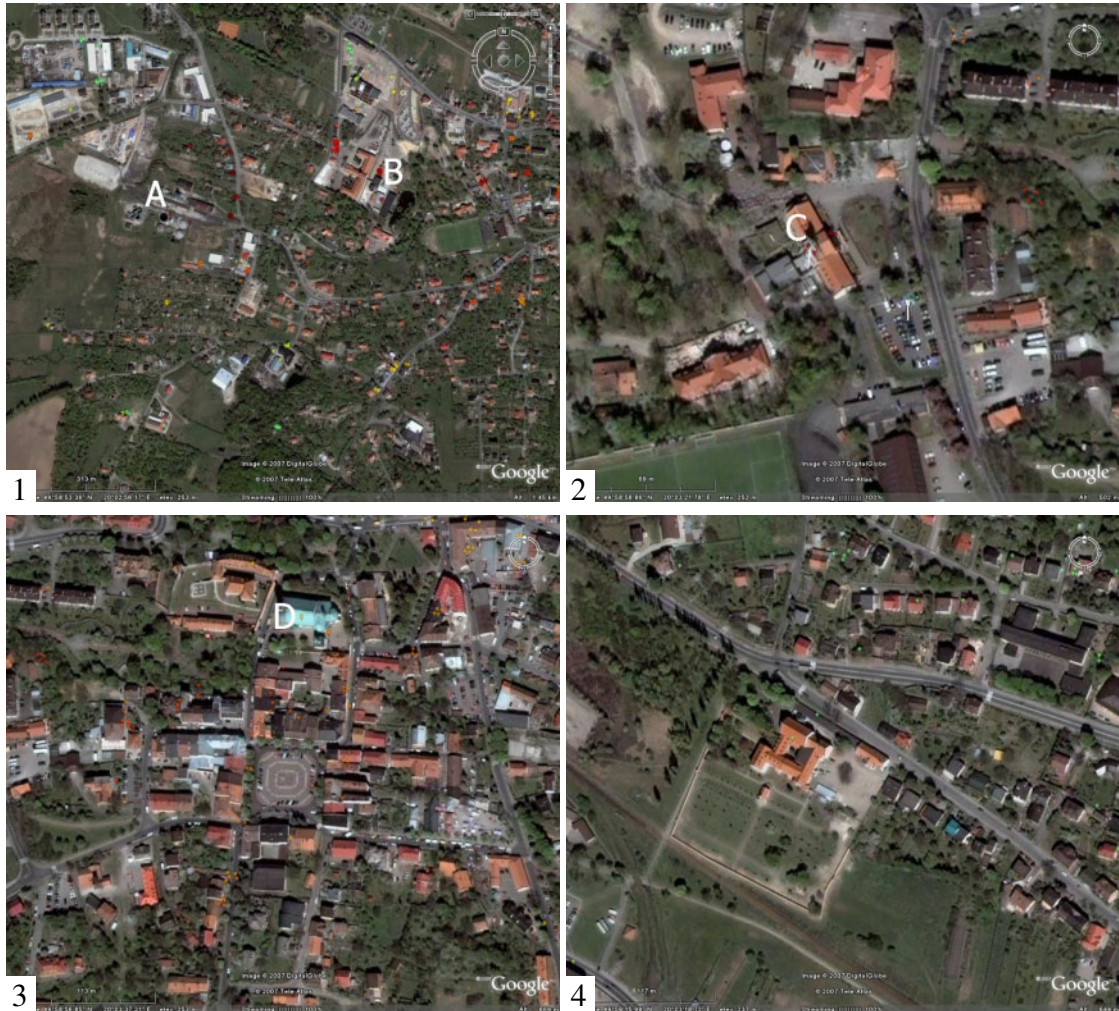


Figure 4. Geo-coded PS distributions in the four areas of Wieliczka with specific linkages to the past and recent salt mine activity. Background optical images are from Google Earth. 1) Area including deep mine shafts Kosciuszko and Kinga; 2) Danilowicz shaft area - main tourist entrance to the mine; 3) Town centre with the oldest min shaft Regis and nearby historical buildings; 4) Area of the Franciscan Monastery (large building in the centre of image). Letters in white indicate the positions of four sample PS, for which temporal displacement trends are shown in Fig. 5.

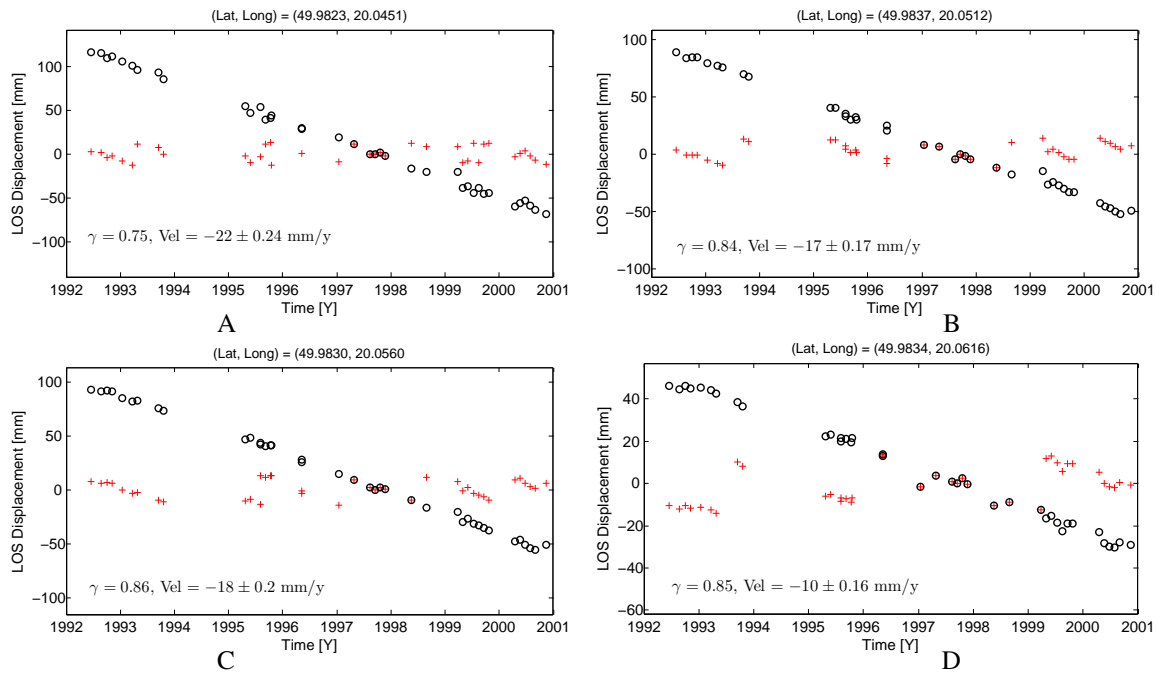


Figure 5. Displacement time series of representative PS indicated in Figure 4. Red crosses and black circles represent wrapped and unwrapped phases, respectively. A: Kosciuszko shaft; B: Kinga shaft; C: Danilowicz shaft; D: Saint Clemens church located very close to the Regis shaft.

(−243 m), and today represents the main tourist entrance (via elevators) to the mine. Here, the PS corresponding to the top of the elevator structure reach velocities of -18 mm/yr. The third area includes the town main square and the oldest and relatively shallow (106 m deep) mine shaft named Regis (Fig. 4-3). The shaft structure itself does not include any radar target, but the PS corresponding to the historical buildings (The Mine Castle and Saint Clemens Church) situated in the immediate vicinity of Regis exhibit velocities ranging from -7 to -10 mm/yr. The last area of particular interest is located to the NW of the town centre and includes the 17th century Franciscan Monastery (Fig. 4-4). In early 1990s, following a sudden, large volume groundwater inflow to the northern part of the mine, the area just south of the monastery suffered from a few meter subsidence and associated landslide phenomena. These events have resulted in the interruption of the railway and damage to the monastery. The PS are notably lacking in the area that has undergone large amount of subsidence and landslide displacements, i.e. south of the monastery. However, the only two PS present in the northernmost part of the monastery appear motionless and thus suggest conditions of stability.

4.3. Wieliczka salt deposit, landslides and PS motion

In order to further interpret the significance of the PSI results in Wieliczka, we examined the geo-coded PS distribution over the geological map that includes also the pre-existing landslides and the areal limits of the salt deposit (Fig. 6). In particular, it is evident that the great ma-

ajority of downward moving PS fall within the Wieliczka area, where the salt has been mined. The western and eastern portions of the salt deposit belt contain very few PS that appear motionless. To the south of the salt belt zone, the Carpathian mountain front slopes facing the Wieliczka mine area are marked by the presence of large, pre-existing landslides. Although there are rather few PS, it is perhaps not by chance that the only landslide that includes some slowly moving PS (from -3 to -7 mm/yr) is the one closest to the zone of maximum subsidence (Fig. 6). These PS straddle the area between the landslide toe, near the slope base, and the southernmost limit of the salt deposit. However, the same landslide in its upper portion contains also non-moving PS. Therefore, at least the following three interpretations are possible: a) the PS movements reflect the mine-induced subsidence that involves also the landslide toe, which overlies the subsiding area; b) the PS movements reflect the true, very slow down-slope displacements of the landslide toe mobilised by the adjacent mine subsidence; c) a combination of a) and b). Regardless the above interpretative uncertainties, there seems to be an apparent link between the Wieliczka depression affected by mine subsidence and the presence of relatively large landslides on the north facing slopes of the Carpathian mountains. It is also possible that the continuous subsidence along the slopes base could lead in the future to partial reactivations of the landslides. Finally, no similar landslides appear to be present on the northern side of the Wieliczka depression. Indeed, this area is characterised by lower elevation hills with gentler slopes.

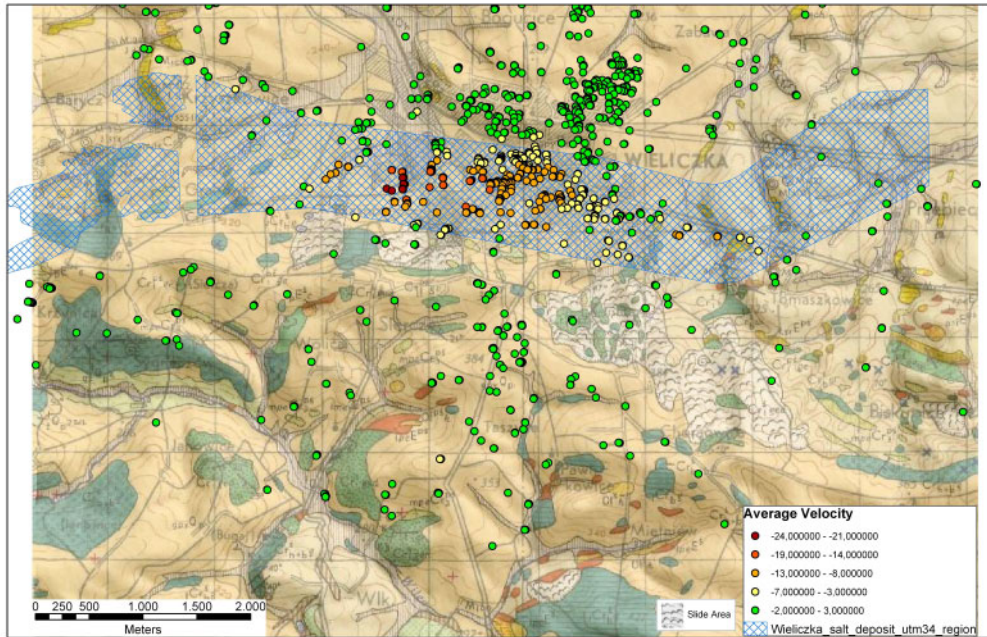


Figure 6. Geo-coded PS distribution superimposed on the geological map (<http://www.pgi.gov.pl>) of the Wieliczka area (draped over a DEM). Salt deposit (blue hatched pattern) occurs within the Miocene age sedimentary units, mantled in the Wieliczka depression by Quaternary sediments. Note also the presence of relatively large landslides on the N-NNE facing slopes of the Carpathian mountain front (involving the Jurassic-Cretaceous flysch units).

5. FINAL CONSIDERATIONS

The application of the PSI SPINUA technique has led to the identification of numerous radar targets (over 100 PS/km²), suitable for ground motion monitoring in the Wieliczka area. The results show the presence of continuous subsidence with average movements ranging from about 1 to 2 cm/yr in the period 1992-2000. The detected width of the subsiding zone corresponds very well to the extent of the underground salt mine, whereas its length (around 4.5 km) is somewhat shorter with respect to that of the mining works and of the known salt deposit. This discrepancy results in part from the lack of suitable radar targets in the rural areas east and west of the town of Wieliczka. The maximum downward displacements are observed in the western part of the town (up to 2.4 cm/yr), where the PS pattern is indicative of the presence of a few km long subsidence bowl. The ground topographic measurements in this area documented about 1 m of subsidence in the period 1970-2000 (i.e. 3 cm/yr). The slightly lower rates of PS displacements revealed for the period 1992-2000 can be in part explained by the ERS satellite LOS geometry. The area to the east of Wieliczka exhibits smaller amount of subsidence (around 1 cm/yr). Although the PS density in the eastern part is not high, their distribution suggests a possible presence of a small subsidence bowl. In addition, the PSI data show locally some significant spatial variations in the amount of downward movements, likely reflecting the differences in the

histories (e.g. depths and modes) of mining operations, variable geological conditions and perhaps also variable structural response of buildings and infrastructures that act as radar targets. There are also indications of the possible linkages between the mine-induced subsidence and the presence of the relatively large landslides occurring on the north slopes facing the Wieliczka area. One of these includes slowly moving PS, but detailed in situ controls would be needed to assess whether these movements reflect the mine-induced subsidence or down-slope landslide displacements or both. Finally, there is evidence that the mining legacy has had a negative influence on the ground and building stability in the town (Fig. 7), which is sited directly above the mine. Therefore, the subsidence hazard to houses and infrastructures in the Wieliczka area should be further monitored. We plan to extend the InSAR monitoring period by exploiting the ENVISAT-ASAR imagery mainly for the urban area of Wieliczka and the ALOS-PALSAR data for the neighbouring rural areas.

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Figure 7. Examples of distressed buildings situated near the main square of Wieliczka.