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Inventory of the geometric condition of inanimate nature reserve Crystal Caves in "Wieliczka" Salt Mine

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Abstract Geological structure of the salt rock mass and its more than 700-year-old exploitation make the "Wieliczka" Salt Mine an important monument of material and natural values. One of the most interesting objects in the mine are the Crystal Caves, which are globally unique, because of salt crystals (halite) which are covering ceiling and sidewalls. Due to its uniqueness, caves are protected by law and a subject of preventive measures. Because of the tightening forces of excavations (convergence) Crystal Caves must be periodically monitored. It is estimated that the speed of convergence is from 0 to 2 mm/year. In order to monitor changes in the geometry of the excavation and deformation of crystals in the 1960s of twentieth century photogrammetric measurements were performed. They require a lot of work and time, and adversely affect the microclimate in the Crystal Caves. Presented in the article modern geodetic measurement techniques (laser scanning, total station) allow to obtain comprehensive data in a short time. It helped to receive an accurate analysis of the changes in geometry of caves. Proposed in the article measurement procedure determines the range of research, which was carried out in order to fully monitor the tested object. Due to the estimated speed of convergence and the accuracy of the applied technologies measurement series on an annual basis are planned. Comparative analysis of the data obtained in the future, give specific conclusions about the current impact of the rock mass on the Crystal Caves and help to improve prevention.

Keywords Crystal Caves · Cultural heritage · Convergence · Geodetic monitoring · Laser scanning

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1 Introduction

The “Wieliczka” Salt Mine is the most famous mine in Poland. It owes its uniqueness in the world to its original geological structure and over 700 years of operation and mining tradition. The history of the “Wieliczka” Salt Mine is inextricably linked with the history of Poland; the mine is a monument of material and natural values. One of the natural reasons for protection of the mine is the great geological diversity within and its differences compared to other salt deposits. Its Crystal Caves are the manifestation of the unique processes of both leaching of chemical residues by circulating water and of secondary precipitation of minerals. They consist of a system of slots and compartments covered with large crystals of rock salt (halite) with edges measuring 10–30 cm (Fig. 1) (Alexandrowicz and Wiewiórka 1994).

These caves is a unique place in the world which require special protection. Thus, for many decades, they have been under special care and have been covered by preventative actions, limiting the impact of external factors to their condition. Above all, these include stabilisation and continuous monitoring of the composition and humidity of air, to prevent leaching of the salt crystals. Unfortunately, the potential movements of salt mass can affect the crystals and side walls of the caves (Markowski 1982). This necessitates geodetic surveys, which allow for determining the current geometric condition of the chambers and for analysing e.g. convergence under selected research profiles.

The uniqueness of the site requires non-invasive methods, which makes it difficult to perform regular checks. Between 1960 and 1980 such surveys were conducted (Borowiec 1974, 1978) using a photogrammetric method, however, they were labour intensive and time consuming. Such methods are not recommended due to existing limitations within the caves. Modern geodetic technologies make use of non-contact laser measurements to determine a distance to the test point. This property was used in the three methods of research: laser scanning, tachometric measurements, and measuring the distance with a laser distancemeter. This enabled verification of measurements and development of hybrid technology for inventory of the current geometric condition of the reserve.

2 Outline of geological structure

In Central Europe, the saliferous formations from the middle Miocene–Badenian, are on both sides of the Carpathians. The chemical residues in Poland remain in the Carpathian Foredeep. It stretches in a narrow belt along the northern edge of the Carpathian mountains

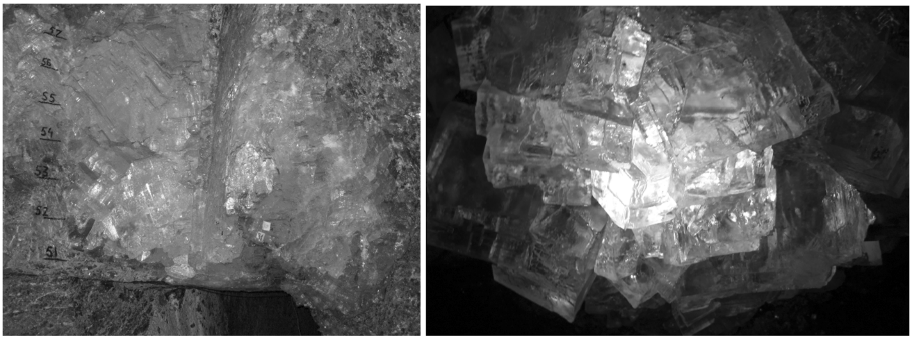

Fig. 1 Halite crystals: *left* on the sidewall of the cave, *right* crystal close-up

from upper Silesia to Cracow, then extends to the north, reaching from Sandomierz to the Carpathian mountains, extending further to Ukraine (Fig. 2). The original thickness of saliferous formations usually does not exceed 50 m. Due to the plastic properties of evaporites and their mobility in conditions of tectonic pressure, the thickness of local chloride facies is much greater (Kortas 2004).

The Wieliczka deposit is located in the western part of the saliferous formation, at the head of the Carpathian overthrust. Its latitudinal extent is approximately 10 km, and the width is in the range of 0.5–1.5 km. Deposit formations belong to a substage of Wielician—the middle part of the Badenian stage—and are referred to as the Wieliczka formation (fm) (Garlicki 1994). It is characteristic that the saliferous formation is dichotomous; there is a stratiform deposit and an overlying boulder deposit (Fig. 3). The stratigraphic profile of the stratiform deposit is made of formations from oldest to youngest: sub-salt clays with gypsum and anhydrite, the oldest salt with strontium and barium minerals, green bed salt, shaft salt (the purest salt available and extracted through shafts) and spiza salts (*sal spissum*—hard salt). Above the bed there is a second complex of saliferous formation—the boulder deposit. It is built mostly by clay-marl deposits called zuber, containing crystals, blocks of salt. The boulder deposit includes several varieties of salt—green laminated (typical green), green large-grained (stained glass salt), rarely striped or dolomitic (Alexandrowicz 2000).

The importance of the Wieliczka deposit is mentioned by Alexandrowicz (1994): “the whole complex of this deposit, with boulders and layers of rock salt and interbeds of gangue, serves as a model and has a rank of a stratotype. It is so regarded in both the

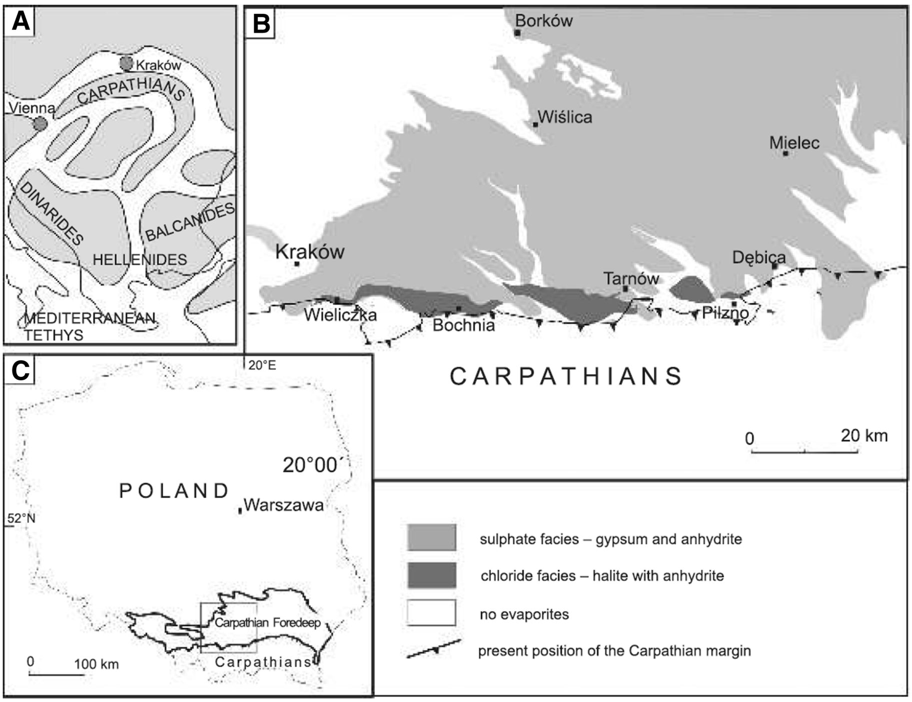

Fig. 2 Location map (*source* Gonera, Bukowski, d’Obryn and Wiewiórka 2012)

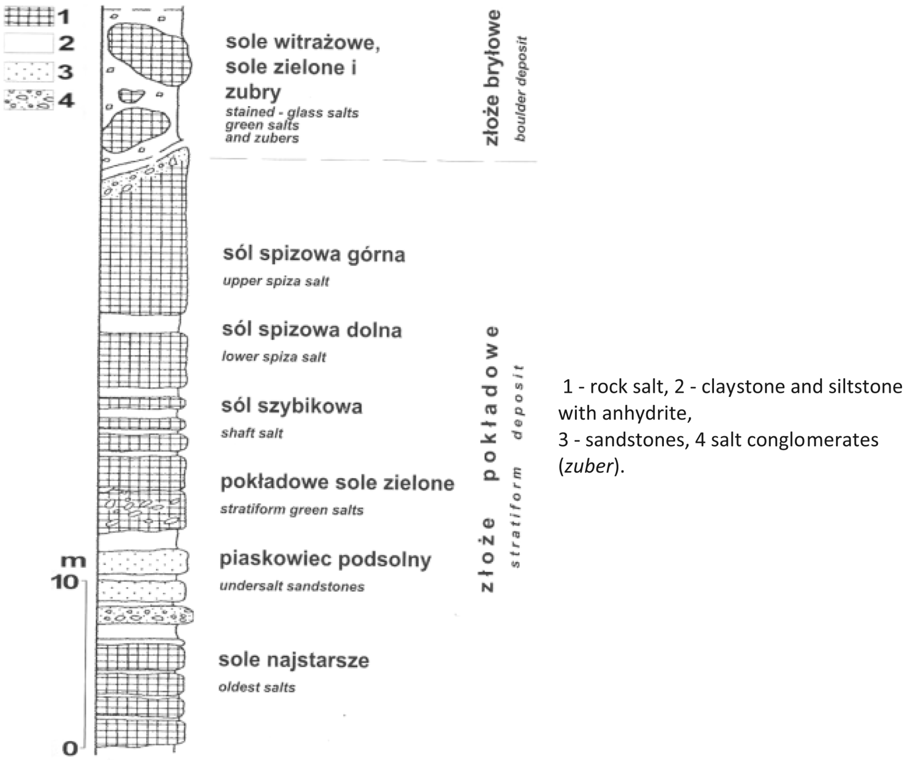

Fig. 3 Lithostratigraphic section of Wieliczka formations (by Galamay et al. 1997)

lithostratigraphic scheme of Polish Miocene, giving these units the importance of the so-called formation of Wieliczka, and in the biostratigraphic division based on foraminifera (microfossils—protozoa of the order *Foraminiferida*), which distinguish the substage of Wielician within middle stage of Badenian".

In the peripheral, northern zone of the Wieliczka deposit, there are the Crystal Caves. They are the manifestation of the unique processes of leaching of chemical residues by circulating water and of secondary precipitation of minerals. The specific environment of this portion of the Wieliczka deposit allowed for the formation of a system of caves, with walls and ceilings covered by halite crystals of considerable size. The Crystal Caves are the grandest of all the currently known examples of Miocene saliferous formations, and therefore deserve special attention and protection.

The salt mass is characterized by a complex internal structure that is also apparent in the area of the Crystal Caves (Fig. 4).

In the described area there is an uplift of the bed deposit rocks and their footwall units (claystone, siltstone and sandstone with gypsum and anhydrite) called the Crystal Caves Dome. The Crystal Caves are located in the northern slope of the dome, in a boulder deposit in contact with the bed deposit (Fig. 5).

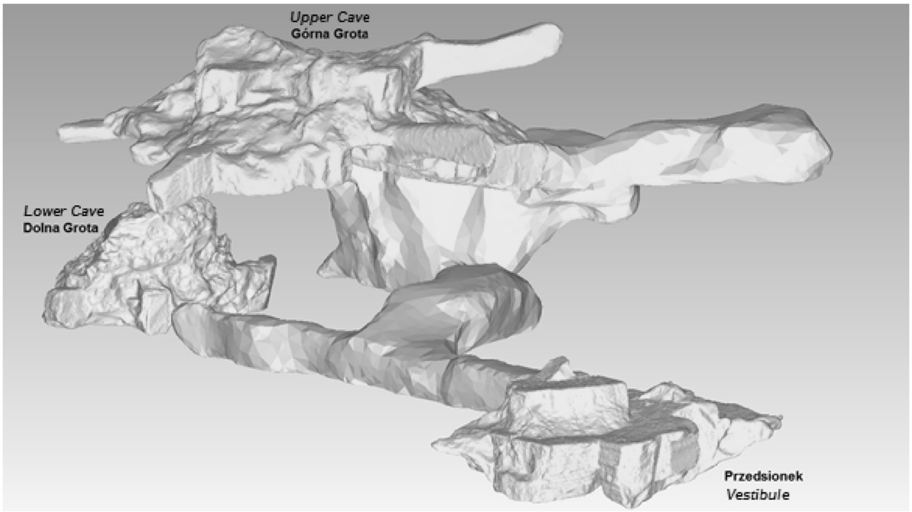

Fig. 4 Spatial configuration of the system of caves comprising the inanimate nature reserve Crystal Caves

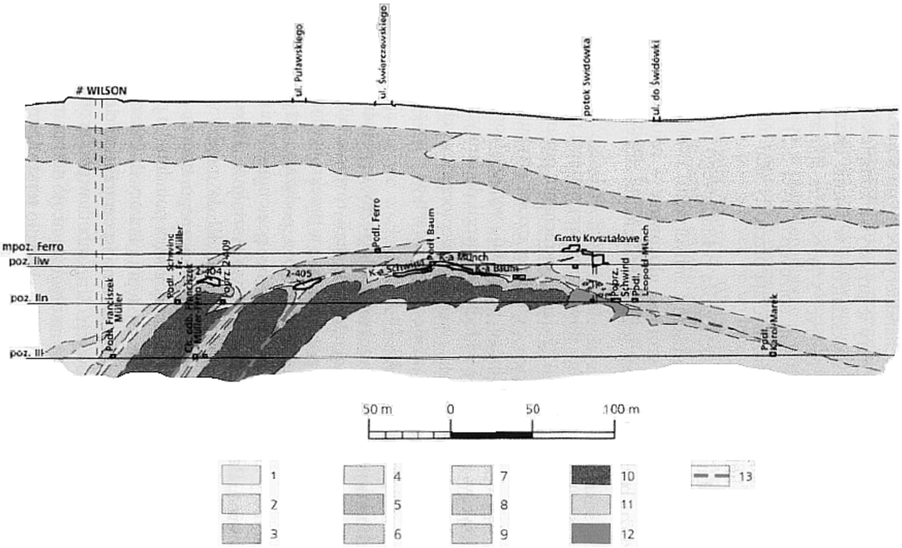

Fig. 5 Geological cross-section through the region of the Crystal Caves; *1–13* geological layers including: *4*—boulder deposit of rock salt and *6*—spiza salt (*source* Alexandrowicz 2000)

3 Design guidelines for geodetic monitoring of the Crystal Caves

There is a lot of methods concerning issues of inventory of caves. Many of conducted works is related with cultural heritage. This works are mostly concentrated on getting the most accurate graphical model of rock art and paintings covering walls of caves (González-Aguiler et al. 2009; Beraldin et al. 2006; Grussenmeyer et al. 2010; Lerma et al. 2010). Ususally at least two technologies are used in such cases i.e. terrestrial laser scanning (triangulation, phase, time of flight) to get the geometry of object and photogrammetry methods for getting textures.

Comparative evaluation of methods for 3D data acquisition (Wong et al. 2011) indicates phase scanner as the most accurate way to get a geometry of an object. Time of flight scanners let to obtain similar results and other methods (stereo cameras, flash lidar, structured light, depth camera) were less precise. Flash lidar or depth camera are characterized by shorter measurement range and the higher accuracy. However, the process of merging individual measurements from different positions also in this methods significantly affects the overall model error. When we take into account an error of registration in our opinion we will get similar or even worse results. For our research the ability to accurately acquire texture wasn't significant, because the most important was a safety of the Crystal Caves related to their convergence (linear, volumetric). The second major threat for the analyzed object was leaching process of salt crystals and its progress in time. But it was not the subject of our research.

The reduction of measuring time was an important issue, because the object is sensitive for humidity and in general isolated from water sources as of main factor causing a leaching of salt crystals. Following the Rüther et al. (2009): "Conventional survey methods would require many thousands of points with which to document the natural and archaeological features within the cave (the cave wall contour, excavation grid, current pock-marked surface topography, stratigraphy of exposed sections etc.) while photogrammetry would have been far more time consuming, both in the field and during processing than the laser scan". To get similar results in relatively narrow excavations connecting grottoes it is necessary to take a lot of pictures which definitely increase measurement time. Dense 3D photogrametry not cope with the uniform textures (like we have in Crystal Caves), while scanning doesn't have this limitation. Dense 3D photogrammetry is in time consuming similar to terrestrial laser scanning but only in terrain work. In dense 3D photogrammetry post processing takes more time because firstly we have to generate 3D data from images while in scanning we get them immediately from scans (every measured point has 3D coordinates). If we are talking about 3D data analysis is possible to compare these methods in terms of time consumption.

The rate of tightening of chambers in a salt mine depends largely on the state of excavations and water hazard, age of the object, operations, depth of excavation, etc. For the "Wieliczka" Salt Mine the estimated speed of convergence was determined with the measuring material from the mine based on measurements of bases in part of the deposit located at depths of 60–200 m below the ground surface. These ranges are from 0 to 10 mm/year. It can be assumed that convergence for the Crystal Caves will be in the range of 0 to 2 mm/year, because this is the range of average convergence for the mine (Hejmanowski 2001). Effective monitoring therefore requires designing a measurement so that the measurement error is in the range of $\pm(1/2)$ mm. With this, the predicted displacement of the object points could be identified with a time resolution of 2 years. However, due to the lack of identification of the speed of convergence, it is recommended to conduct subsequent series of measurements at intervals of not more than 1 year. This will allow the estimation of the actual speed of convergence, and most importantly-will allow for the possible detection of areas where it occurs faster than expected.

A study of convergence with such accuracy requires clearly identifiable points which will comprise of end points of bases. Due to the nature of the object it was not possible to use classical stabilisation of points in the pit ceiling. Stabilised points were placed at the base of the excavation and the smallest possible number of points was stabilised so as to limit interference with the object. Several measurement points were established in the form of footwall points and targets affixed to sidewalls and the ceiling in order to register the process of horizontal and vertical convergence. Stabilised marks allow for the unique determination of their spatial position. To enable control of movements of ceiling, particularly in the areas of halite crystals, it was necessary to mark the controlled points. For this purpose we used photogrammetric stamps from measurements performed in the 1970s (Borowiec and Mikołajczak 1977; Borowiec and Batko 1979) and also placed a few more. Newly placed marks are black and white checkers, typically used to register cloud points in terrestrial laser scanning.

They allowed for defining the following number of bases, presented in Fig. 6:

1. Vestibule—three horizontal bases (KP) and two vertical bases;
2. Lower caves—two horizontal bases (KD) and three vertical bases;
3. Upper caves—six horizontal bases (KG) and four vertical bases.

Repeated measurements for the bases will allow for the evaluation of the rate of tightening of the formation, both in the vertical line as well as in planes similar to the level and setup of indicators of the deformation.

Projected accuracies of determination of the length of bases are consistent with current accuracies of reflectorless distance measurement. It was therefore decided to use the three instruments allowing for such measurement in monitoring, i.e. The Leica Disto D3a BT laser distancemeter, Total Station Topcon GPT-7505 and a panoramic scanner Faro Focus 3D 120.

The use of reflectorless distance measurement (with laser distancemeter) results in two important problems in terms of accuracy. The first is the problem of identifying the point to which the distance is actually measured. However, when using a total station and short lines that are measured in the object, this problem is not critical. The scanner however

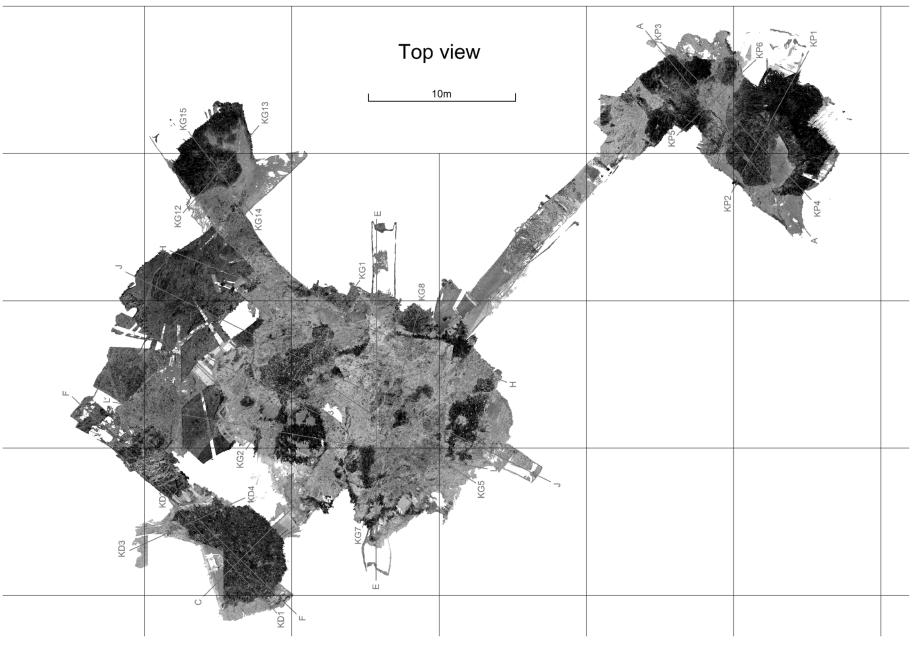

Fig. 6 Orthogonal projection from the top of the "Crystal Caves" with marked horizontal bases

should have properly adjusted measurement resolution, so that identification error for cloud points had no significant impact on the determined length of the sides of the bases. In the case of the DISTO distancemeter, the problem of identification of the target is negligible. However, one should take into account the measurement uncertainty associated with accuracy of aiming, because the distancemeter is set and controlled manually (Joint Committee for Guides in Metrology 2008). In order to minimize the impact of this factor, it was decided that one person will set the distancemeter using a mini-stand and another person will remotely take the measurements using an application on a mobile phone. In conjunction with repeated (for control) measurement of each base length, it brought good results.

The other major problem associated with the distance measurement accuracy is related to the angle of incidence of the laser beam on the target surface. Unfavourable angles of incidence of the beam (far from perpendicularity) cause systematic distance errors. This problem is solved by independent determination of base distances using various instruments with variable settings of the angle of incidence of the laser beam on the surface (different positions of total station and scanner, direct measurement of the distance using a distancemeter). The comparisons of the values of the distance from measuring with instruments allow for detecting possible outliers and exclude them from further processing.

The observations were therefore designed to exclude the possibility of systematic errors and outliers and minimize the impact of random errors. The shape of the Crystal Caves was determined by laser scanning while the spatial coordinates of controlled points were defined in two ways: with classical measurements (surveying, levelling) and laser scanning. The measurement methods complement each other and allow for unambiguous and accurate determination of the length of the base sides. In addition, the scanner allowed for slightly less accurate, but a complete geometric inventory of the object.

4 Measurement and analysis of results of geodetic measurements

The monitoring covered the entire Crystal Caves, i.e. the vestibule (A), the lower cave (B) and the upper cave (C). This chapter describes the method of analysing control base measurement results together with the analysis of accuracy and total inventory of the object using a laser scanner.

4.1 Inventory of the object using a laser scanner

A control points was set up in the object for the purposes of inventory; the horizontal reference network was measured using the total station Topcon GPT-7505, and altitude reference network was measured using the Leica DNA03. The reference network was determined in the form of traverse tied at one end. Heights were connected to the benchmark located at the pit bottom of the Wilson shaft, and horizontal connection was made to points of the mine measuring network located approximately 300 m from the Crystal Caves. The angular-linear measurements were performed with using the method of three tripods centring, due to the inclusion of temporary points to the traverse.

During measurement of the control points using the total station, we also determined coordinates of targets necessary for scans registration and determination of coordinates of the merged cloud points in the mine coordinate system.

A complete inventory of the object was carried out using the Faro Focus 3D laser scanner. Scans were performed in the angular resolution of 4 mgon, which gives a density

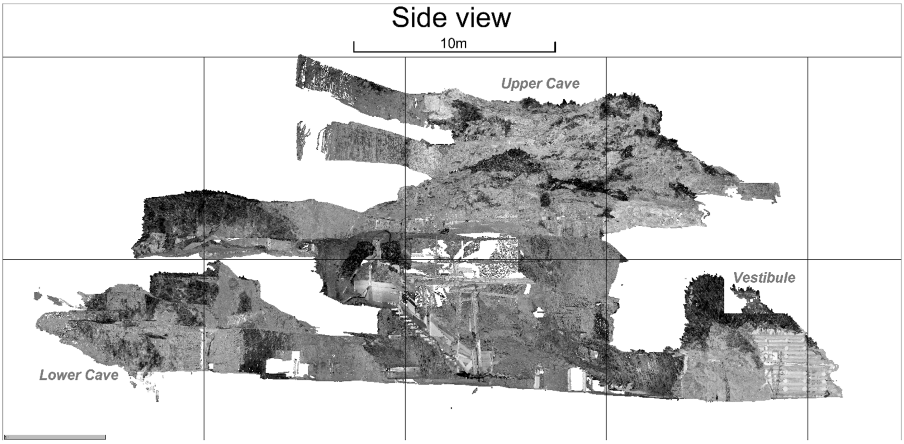

Fig. 7 Orthogonal projection of the Crystal Caves from the side

of measurement points of 3 mm/5 m. Scans from individual positions were registered based on the coordinates of targets, which were determined using the total station Topcon GPT-7505. We did not use the so-called "cloud to cloud" registration due to the unfavourable (for this purpose) geometry of the object. The accuracy of this inventory can be characterized by the position error of each cloud point and the influence of range measurement noise. It is proved that in methods based on laser beam the worse signal reflectance the higher ranging noise. Registered reflectance should also be taken into account during analysis of deformation. The value of this error is of the order of 5–10 mm for areas not occupied by crystals (sidewalls, footwall, part of the ceiling). In the case of salt crystals it was impossible to accurately determine their geometry (with the exception of base end points) using scanning, as the degree of penetration of the laser beam through the crystal greatly depends on the transparency, the crystal structure and the angle of incidence of the laser beam. Hence, when measuring position of crystals with a scanner, the measurement noise can have very large values of even a few centimetres. Analysis of this phenomenon is the subject of the article under preparation. An orthogonal projection from the side, drawn on the basis of the registered point cloud is shown in Fig. 7. It should be noted that the making of orthogonal projections and sections is only part of the possibilities of using scan results, because each point has known spatial coordinates. It is therefore possible, based on data obtained, to determine e.g. mutual position of arbitrarily selected points (elements of the object). In the longer term, it will be possible to determine the spatial deformation of the object (displacement), which would be virtually impossible to achieve in such detail (high resolution) using conventional measurement techniques. This analysis will be possible after comparing spatial models (Fig. 8) made in subsequent research cycles. One can also compare raw point clouds—but for practical reasons it is less convenient in terms of analysing the data than the analysis of developed layer models.

4.2 Classical surveying

Site measurements were based on the determination of angles and distances in the traverse using electronic total station Topcon GPT 7505, with three tripods centring from points

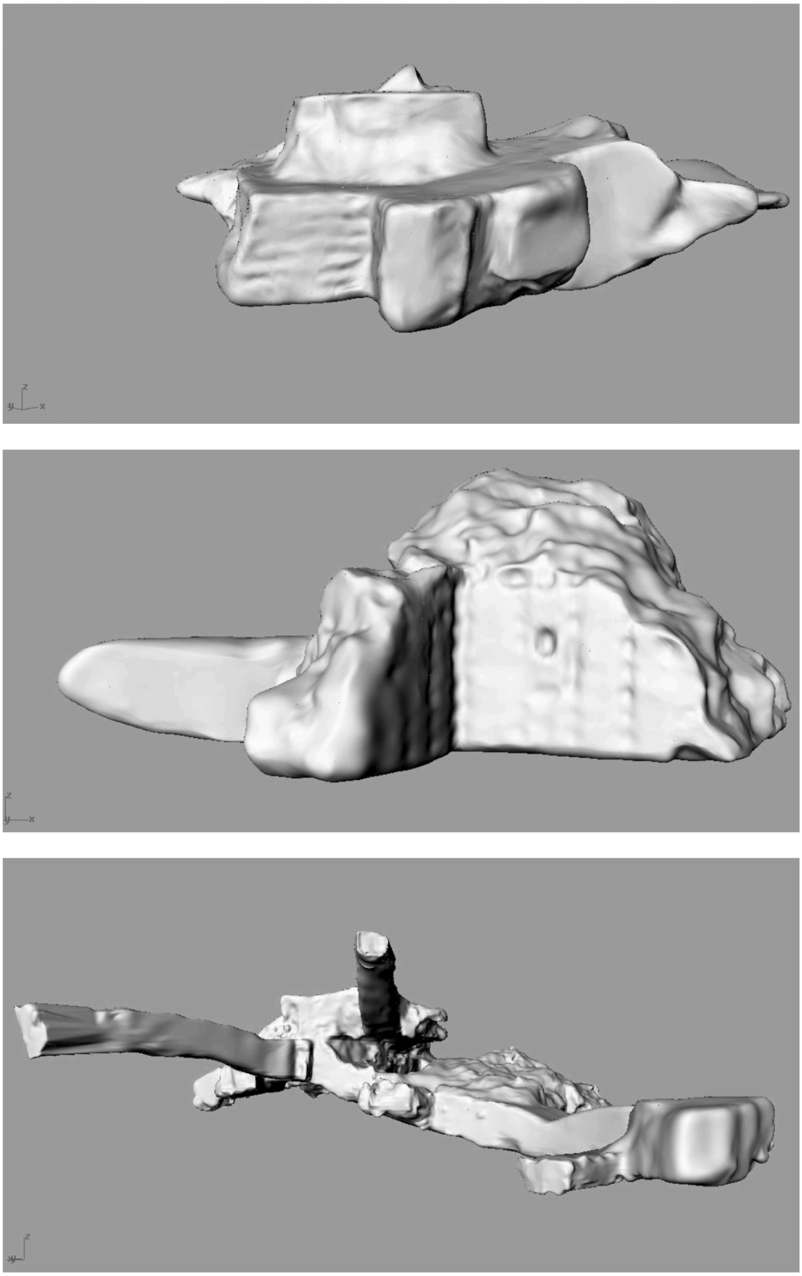

Fig. 8 Spatial models of Crystal Caves based on laser scanning

numbered 221061, 221060, 221092 to marked points in the Crystal Caves (Fig. 9). The accuracy of the determined horizontal coordinates is in the range from ±1 to ±6 mm (at the end of the traverse), which means the compatibility of measurement with the

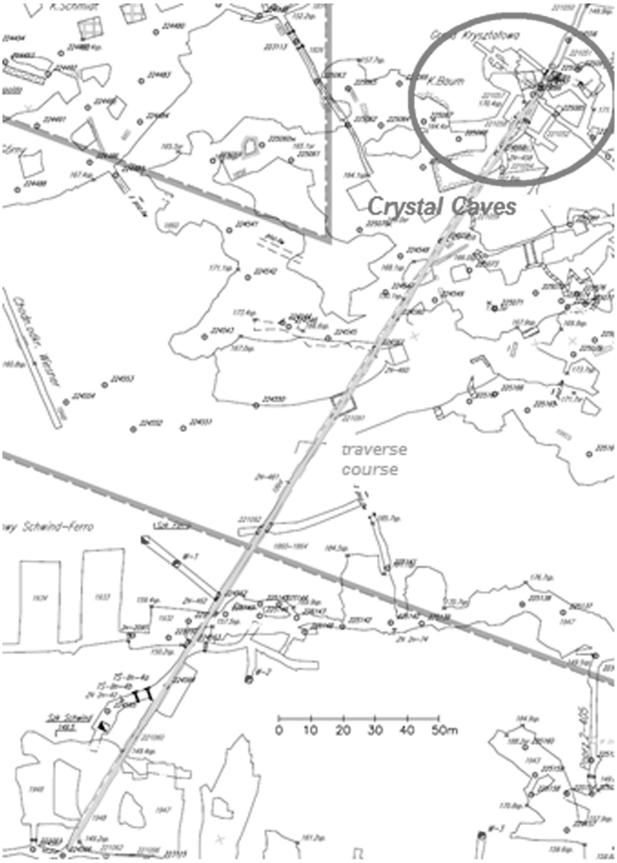

Fig. 9 Connection of horizontal measurement

preliminary analysis performed previously (horizontal position standard uncertainty of end point in the traverse is ±8 mm).

There have also been observations in the form of geometric and trigonometric levelling in order to determine the height of all network points and bases terminals. Levelling was carried out in both directions (back and forth) with precision leveller DNA 03 with code rods. The method of geometric levelling allowed determination of heights of network and controlled points. The point for connecting height was the benchmark set at the Wilson shaft with number ZN 2n-62 (Fig. 10). Due to the adverse conditions of the geometric levelling between levels, trigonometric levelling measurements were conducted on three sides, binding geometric levelling lines. The standard uncertainty of the height difference by trigonometric levelling was about ±2 mm for each measured section. Height measurements were implemented in accordance with the assumed technology, obtaining a standard uncertainty for height in the network of ±1.3 mm. This demonstrates that objectives set out in the preliminary analysis were met.

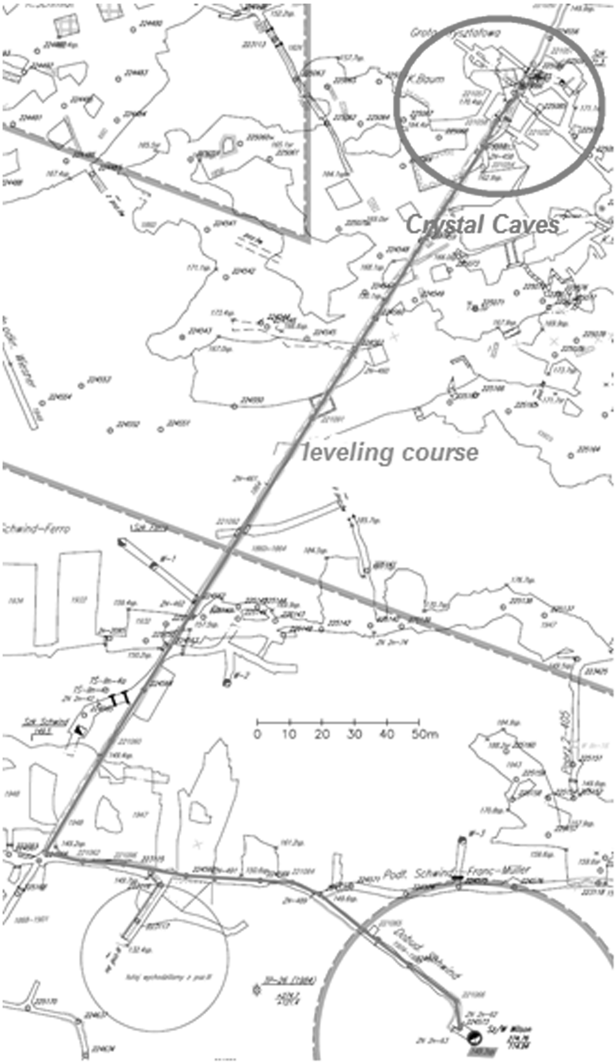

Fig. 10 Connection of height measurements

4.3 Determination of the lengths of control bases

A total of 21 control bases were established to allow for accurate determination of the convergence of the monitored object, including ten vertical bases and 11 horizontal bases. Location and orientation of control bases in space is shown in Fig. 6 (horizontal bases). The range of bases lengths is from about 2 to about 12 m, and the average length is about 5 m.

Length measurement of control bases were made using three instruments, i.e. a laser distancemeter Leica Disto D3a BT, a Faro Focus 3D 120 scanner and a total station Topcon GPT-7505. The number of bases measured with a given instrument is summarized in Table 1.

Table 1 List of control bases measured with various instruments

Instrument	Number of determined lengths for control bases	
	Vertical	Horizontal
Leica Disto D3a BT	10	0
Faro Focus 3D 120	10	11
Topcon GPT-7505	4	11

Table 2 Summary of average differences in determining the lengths of control bases depending on the instrument used

Instruments	Average value of differences (mm)	Number of averaged differences
Leica Disto D3a BT—Faro Focus 3D 120	2.2	10
Leica Disto D3a BT—Topcon GPT-7505	3.0	4
Faro Focus 3D 120—Topcon GPT-7505	4.2	15

Length of bases was determined directly using a Leica Disto distancemeter, while the scanner and total station were used to determine them on the basis of the determined coordinates according to the relationship:

$$D = \sqrt{\left(X_k - X_p\right)^2 + \left(Y_k - Y_p\right)^2 + \left(H_k - H_p\right)^2} \tag{1}$$

where X_p, Y_p, H_p—Cartesian coordinates of the starting control point in base; X_k, Y_k, H_k—Cartesian coordinates of the end control point in base.

The locations of bases terminals were always measured so that both ends are measured from a single instrument station. Table 2 shows average values of the differences between the determined lengths of control bases according to the instruments used. The maximum discrepancies between the lengths reach 7 mm in individual cases. This was associated with random errors connected to point identification, which were eliminated by redundant measurements.

A simplified analysis of the accuracy based on the law of propagation of uncertainty leads to the following formula for combined standard uncertainty of determining length of bases using a total station and a scanner:

$$m_D = \sqrt{2} m_d \tag{2}$$

where m_D—standard uncertainty of determining the length of base using a given instrument; m_d—standard uncertainty of length measurement using a given instrument.

This assumes that the spatial angle between lines to the ends of base is close to 180°, which is the case for most of the determined bases. This is because the length error in the direction of base has a significant impact on the accuracy of determining length of bases. The effect of errors in measured directions using a total station is negligibly small (very short lines, accuracy of determining the direction of the order of 5″). In the case of the scanner, the assumption concerning angles between lines is also satisfied, and additionally coordinate precision is maintained between the angles and lengths, which further justifies the adoption of the proposed approximate formula.

Table 3 Summary of nominal accuracy of distance measurement and accuracy of length measurement of bases using the instruments

Instrument	Nominal mean square error in distance measurement (mm)	Mean square error in determining length of base (mm)
Leica Disto D3a BT	1.0	1.5
Faro Focus 3D 120	2.0	3.0
Topcon GPT-7505	3.0	4.2

The value of standard uncertainty of length measurement using the Leica Disto distancemeter should take into account not only the nominal accuracy of determining length with this instrument, but also the aiming error. The value of standard uncertainty in this case was estimated based on the measurement material (type A evaluation of uncertainty). There were at least few repetitions, so as to achieve convergence of at least three results (within 2 mm), which allowed the adoption of the average of these results as the final value.

The accuracies of determining the distances with measuring instruments used are summarized in Table 3. The actual registered discrepancies between the lengths of control bases generated using different instruments (Table 2) are consistent with the values estimated based on the described accuracy analysis (Table 3).

Taking into account the accuracy of determining lengths of bases with various instruments, the weighted mean was assumed as the most likely value:

$$\overline{D} = \frac{W_D D_D + W_F D_F + W_T D_T}{W_D + W_F + W_T} \tag{3}$$

where W_D, W_F, W_T—accordingly, the weights of lengths determined using a Leica Disto D3A BT distancemeter, Faro Focus 3D scanner and total station GPT-7505; D_D, D_F, D_T—accordingly, the lengths determined on the basis of observations using a Leica Disto D3A BT distancemeter, Faro Focus 3D scanner and total station GPT-7505.

The weights should be proportional to the (inversion of) squared standard uncertainty, but for the sake of simplicity and taking into account uncertainity of estimation of standard uncertainty values it was assumed for calculations that

$$W_F = W_T = 1; \quad W_D = 2$$

In the case of significant discrepancies between one of the methods and the others (i.e. the difference between the lengths of $\geq$4 mm) or lack of observation for the given method of determining length of base, the assumed weight was zero. Application of the law of propagation of uncertainty to the formula for the most probable value of observation allows for determining the relationship:

$$m\frac{2}{D} = \frac{1}{4}m_D^2 + \frac{1}{16}m_F^2 + \frac{1}{16}m_T^2 \tag{4}$$

for the length of control base determined using all three methods, and:

$$m_{FT}^2 = \frac{1}{4}m_F^2\frac{1}{4}m_T^2 \tag{5}$$

for the measurement using only a scanner and a total station.

The analysis using the above formula leads to determination of the standard uncertainty value of about ±1.5 mm, as measured by all methods used. When measuring using only a scanner and a total station (horizontal base), the standard uncertainty has a value of about ±2.5 mm. Conducting redundant measurements using several different instruments increases the reliability of the result in terms of elimination of outliers and systematic errors whose sources are described in an earlier chapter. The resulting accuracy of determining lengths of bases is consistent with the design assumptions.

5 Conclusions

Conducted geodetic observations are a preliminary stage for periodic determination of deformations of the Crystal Caves. Therefore, it is necessary to perform subsequent measurement series in periods allowing for determining the significant values of displacements, and on this basis, determining the so-called indicators of deformation.

The use of laser scanning allowed for development of a complete documentation of the shape and dimensions of the Crystal Caves complex. It would not be possible using other measurement techniques, except for photogrammetric techniques. However, this would require significantly more work and time needed to achieve a similar result.

The determined standard uncertainties (σ) of horizontal coordinates of control points do not exceed 6 mm relative to the connection points located near the Wilson shaft, but the mutual positions of test points arranged in the chambers is not determined worse than (1/2) mm using direct measurements. According to literature on surveying (Węzony 1990; Pielok 2002), it is assumed that displacements take significant values (subject to interpretation) over three times the standard uncertainty (expanded uncertainty). In case of periodical measurements, the threshold may be lowered to twice the value of this measure. Assuming the limiting error criterion of 2σ, all changes after exceeding the value of 4 mm should be considered as significant. The similar analysis of height measurements shows that the standard uncertainty in determining the height of a point is about 1.5 mm in connection to the benchmark ZN 62 located at the Wilson shaft. On this basis, it can be considered that changes above (3/4) mm are significant.

Height measurements made in conjunction with laser scanning allowed for determining the height of the benchmark in the upper cave ($H = 178.006$ m), which compared to previous measurements made in 1992 ($H = 178.018$ m) and 2003/04 (178.020 m) means a reduction of about 14 mm during the past 10 years. It follows that the speed of subsidence in 1 year is about 1.4 mm. This value is similar to the determined annual rate of subsidence in the area of the Wilson shaft (2 mm/year) and to the specified value for the speed of convergence in 2005/2010 (from 0.1 to 1.4 mm/year). Assuming the criterion of significance of changes at the level of 4 mm, this means that there is a need to perform observations at least every 3 years. However, due to the unique nature of the Crystal Caves from the perspective of cultural and natural heritage, as well as due to the performance of initial series to which subsequent observations will apply, it is suggested that a second series of measurement should be performed in 2015, and other at intervals of 2–3 years.

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