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DETERMINATION OF GRANITE ROCK MASSIF WEATHERING AND CRACKING OF SURFACE LAYERS IN THE OLDEST PARTS OF MEDIEVAL MINE DEPENDING ON USED MINING METHOD

OKREŚLENIE GRANIC WIETRZENIA MASYWU SKAŁ GRANITOWYCH I SPĘKAŃ WARSTW POWIERZCHNIOWYCH W NAJSTARSZYCH CZĘŚCIACH ŚREDNIOWIECZNEJ KOPALNI, W ZALEŻNOŚCI OD STOSOWANYCH METOD WYDOBYCIA

The paper presents the use of selected non-destructive testing methods for the purpose of specifying information on weathering and cracking of surface layers of granite rock massif in the medieval Jeroným Mine (the Czech Republic). This mine has been declared the National Heritage Site of the Czech Republic and its opening as a mining museum to the public is gradually prepared. Geological and geomechanical evaluation documents the possibility to find all kinds of weathering grades of rock massif in this mine. Two non-destructive methods have been tested, namely the measurement of ultrasonic pulse velocity and the measurement of Schmidt hammer rebound value. Field measurements were performed in two selected galleries to verify the application of such methods in specific conditions of underground spaces. Used mining method is one of the parameters later influencing cracking of rock massif. In selected galleries, two different mining methods were used which means that a part of a gallery profile was mined out by hand tools in the Middle Ages and another part of the profile was later mined out by blasting. Measurements in these galleries have enabled to analyse the influence of used mining methods on cracking of rock massif in the impaired zone, and, consequently, on ongoing weathering processes in those zones.

Keywords: Jeroným Mine, non-destructive testing, ultrasonic pulse velocity, Schmidt hammer, weathering, granite

W pracy omówiono wykorzystanie wybranych metod nieniszczących w celu zebrania szczegółowych danych na temat wietrzenia skał i pękania warstw powierzchniowym w masywie skał granitowych w średniowiecznej kopalni Jeronym (Republika Czeska). Kopalnia ta została wpisana listę obiektów dziedzictwa narodowego w Republice Czeskiej, obecnie trwają przygotowania do jej otwarcia jako muzeum górnictwa, dostępnego dla zwiedzających. Analizy danych geologicznych i geochemicznych potwierdzają możliwość postępującego wietrzenia masywu skalnego. Przetestowano dwie metody nieniszczące: pomiar prędkości impulsu ultradźwiękowego oraz pomiarów reakcji po odskoku po uderzeniu młota Schmidta. Badania terenowe przeprowadzono w dwóch chodnikach w kopalni w celu weryfikacji metod zastosowanych w szczególnych warunkach przestrzeni podziemnych. Wybór metody wydobycia jest podstawowym

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czynnikiem warunkującym powstawanie spękań górotworu. W wybranych chodnikach zastosowano dwie różne metody wydobywania: w jednej części urabianie odbywało się za pomocą narzędzi ręcznych stosowanych w Średniowieczu, w części drugiej urabianie prowadzono przy wykorzystaniu prac strzałowych. Pomiary wykonane w obydwu chodnikach umożliwiły zbadanie wpływu metody wybierania na pękanie górotworu w sąsiadujących strefach, a także na postępujące procesy wietrzenia skał w tych rejonach.

Słowa kluczowe: kopalnia Jeronym, metody nieniszczące, pomiar prędkości impulsu ultradźwiękowego, młot Schmidta, wietrzenie skał

1. Introduction

Non-destructive testing methods are popular when investigating properties of different materials. Their advantage is primarily in obtaining the information on materials without damaging them visually. Many methods are used both in field survey and in laboratory conditions for testing specimens (Fitzner, 2002). The selection of a suitable testing method is based on the investigated parameter of a material and on possibilities to use a selected method in an investigated place. Problems of gradual degradation and subsequent destruction of rock materials are mainly solved in historical buildings, monuments and works of art. We may also encounter these problems in specific structures found in rock massif such as underground historical artificial spaces e.g. tombs, crypts and historical mine workings. Many of these historical spaces are declared cultural heritages and it is necessary to explore them non-destructively. Especially in underground spaces of a complex structure in difficult geological conditions it is necessary to protect them against gradual destruction by using stabilizing and treatment methods. In such cases it is necessary to find a compromise how to stabilize the structure, and at the same time preserve the most valuable parts in original state.

The shallow medieval mine is an example of a structure found in rock massif. The Czech Republic has had a long mining tradition and mining activities have been carried out in different locations. The Jeroným Mine, situated in the Western part of the Czech Republic, is a valuable example of preserved historical mining operations dating back to the 16th century and it represents a part of the European Mining Heritage Network. The oldest parts of the mine are related to the extraction and processing of tin. Historical handmade underground spaces such as chambers and galleries are the most preserved in the central Europe (Fig. 1). In the underground complex we can find mine workings made by different mining methods such as extracting by a picker and miner's hammer, fire-setting, underhand stoping or overhand stoping, chamber mining, etc. Nowadays, this mine is declared the National Heritage Site of the Czech Republic and its opening to the public, as a mining museum, is gradually prepared. Stability of the mine, the parts of which are more than 400 years old, is the priority both in the light of preserving the unique spaces for next generations and in the light of safety of people visiting the mine. The evaluation of stability from the viewpoint of geomechanics can be found in several papers, e.g.: (Žůrek & Kořínek, 2001/2002; Kaláb et al., 2008; Knejzlík et al., 2011; Lednická & Kaláb, 2013a). Historical spaces in the oldest parts of this mine are so valuable that it is necessary to carry out all the investigation without any visible destruction of these places. In previous studies (Lednická & Kaláb, 2012; Lednická & Kaláb, 2013b), the possibility of using non-destructive methods for testing rock massif directly in the mine was described. As mentioned in these studies, one of the parameters, influencing weathering of surface layers of rock massif underground, is a type of used mining method. Each of mining methods used in that mine, had a different principle of rock massif cracking and each of the methods caused a different extent of cracked zone around mined out spaces.

In this paper, two non-destructive methods were used to characterize weathering grade of rock massif and cracked zone along profiles of selected galleries. The galleries were mined out by hand tools during the oldest period of mining activities in this locality, and later they were extended by blasting operations along one side of gallery. Changes of rock massif quality (depending on used mining method) at the gallery profile are studied.

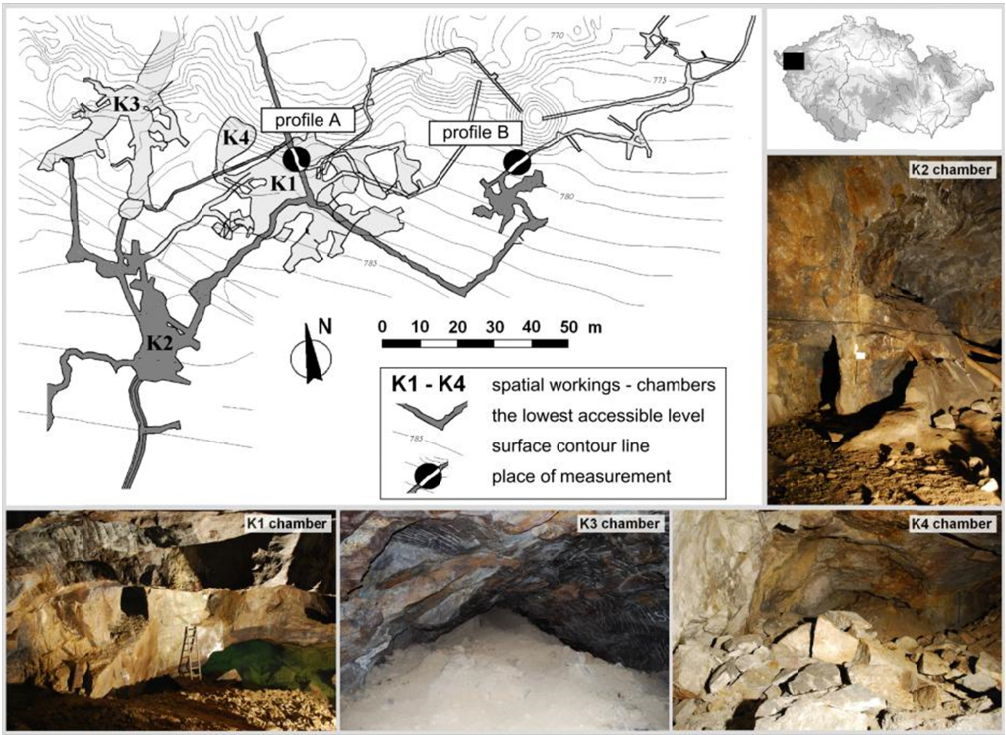

Fig. 1. Sketch of the Jeroným Mine and photos taken in the spatial workings of the mine (*photo*: Lednická)

2. Locality description

The Jeroným Mine is located near the former Čistá municipality (also known as Lauterbach Stadt) in the Sokolov District, the Czech Republic. The locality is a part of protected landscape area, the Slavkovský Les Mountains. The locality has a dramatic history due to the loss of population after World War II, due to the opening of military training camp, due to the demolition of historical Lauterbach Stadt and uranium mining (Raška & Kirchner, 2011). At present, the Jeroným Mine is included in the Czech Bavarian Geopark (www.geopark.cz) as one of the most valuable locality.

From the geological viewpoint the territory consists of metamorphosed rocks of the Slavkov mantle crystalline complex and of Variscian granites of the Ore Mountains pluton. Rock massif underground had been exposed to devastation and weathering for many years and places with lower stability were formed as a result of those processes. Some critical places underground are represented mostly by fissured and weathered supporting pillars or hanging layers on the roof in chambers. The Jeroným Mine consists of an underground system of workings, galleries, shafts and chambers on at least three horizontal levels in the depth ranging from 50 to 10 m below the surface. The lowest level is permanently flooded and its scope is unknown. All historical maps and documents were destroyed by the fire in the Bureau of Mines in the 18th century. The oldest known map displays a sketch of the Jeroným Mine in 1891. Other maps are known from World War II, when German companies lead the exploration and mining activities in this mine. In this period, some parts of the mine were re-discovered and new galleries were also driven.

3. Mining methods used in the locality and their effect on weathering processes

Cracking of rock massif is realized during mining to obtain better workability of rocks. In the oldest stages of mining in the Jeroným Mine, which began in the 16th century, hand tools were used for crumbling away the rock. Using this mining method, the rock cracked only in the contact zone of a hammer with the rock; the formation of cracks in a surface layer of rock massif was negligible. The principle of rock ruptures in the contact zone of a hammer with the surface of rock material during manual work is shown in Fig. 2. Surfaces formed like this have been preserved so far in the majority of historic parts of the Jeroným Mine and they have become the most valuable from the historical point of view. Typical examples are galleries with space-saving profile where the height is only about 1.5 m (see the example in Fig. 5a,b).

Fig. 2. Principle of rock ruptures after hammer blow (according Lehrberger & Gillhuber, 2007): (1) crushed zone, (2) cracked zone – radial cracks, (3) abruption of fragments; photos illustrate examples of mined out spaces using hammer blow in the Jeroným mine (*photo:* Lednická)

Another method, used in the oldest stages of mining in the deposit, is called fire-setting which consisted in heating the rock using kindled logs (Agricolae, 1556). When the temperature changes, various minerals are subjected to volume changes at various speed resulting in development of stress at the boundaries among individual minerals. As a result, the surface layer of the rock cracked and it was easier to cleave it by iron tools. Typical phenomenon is the rest of soot on the roofs and walls of mine workings, which were used for fumes ventilation (Fig. 3).

Fig. 3. Principle of fire-setting (according Agricolae, 1556): (1) kindled logs, (2) heap of dried logs, (3) fumes ventilation; photo illustrates an example of the rest of soot on the roof of gallery (*photo:* Lednická)

Drilling and blasting operations, used in the deposit probably from the 19th century, impacted considerably on the deterioration of surface layers of rock massif. The depth of impaired zone (cracked zone, Fig. 4) depends on a number of parameters, e.g. quasi-static pressure on the wall of the hole, tensile strength of rock, hole radius, detonator charge radius, detonation velocity, rock density (Li et al., 2009). The purpose of blasting was to expand the original old space-saving profiles of galleries, or extraction in chambers and making new galleries. Blasting operations were also used in the 20th century during World War II, and probably in the course of the exploration in the 1960s.

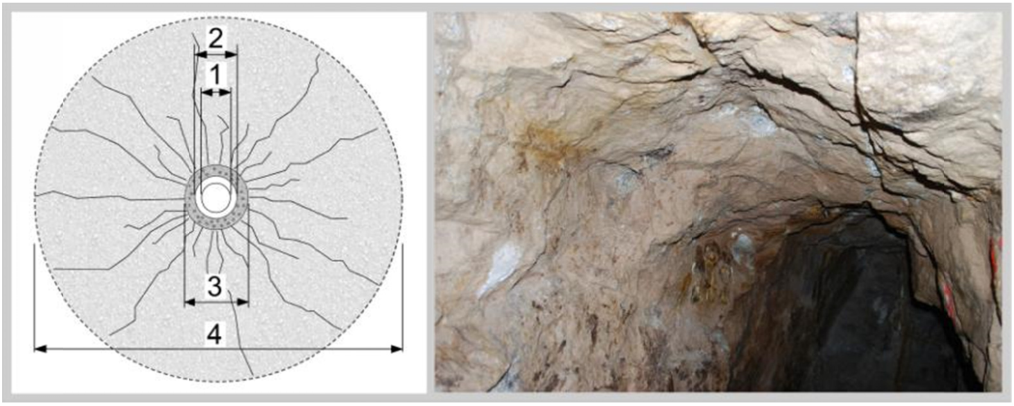

Fig. 4. Principle of rock ruptures around a blasthole (according Li et al., 2009): (1) borehole, (2) bulge, (3) crushed zone, (4) cracked zone; photo illustrates roof of the gallery made during World War II using blasting (*photo:* Lednická)

Some examples of galleries driven by different methods are presented in Fig. 5. There are examples of galleries made by hand tools, by blasting and by a combination of both methods.

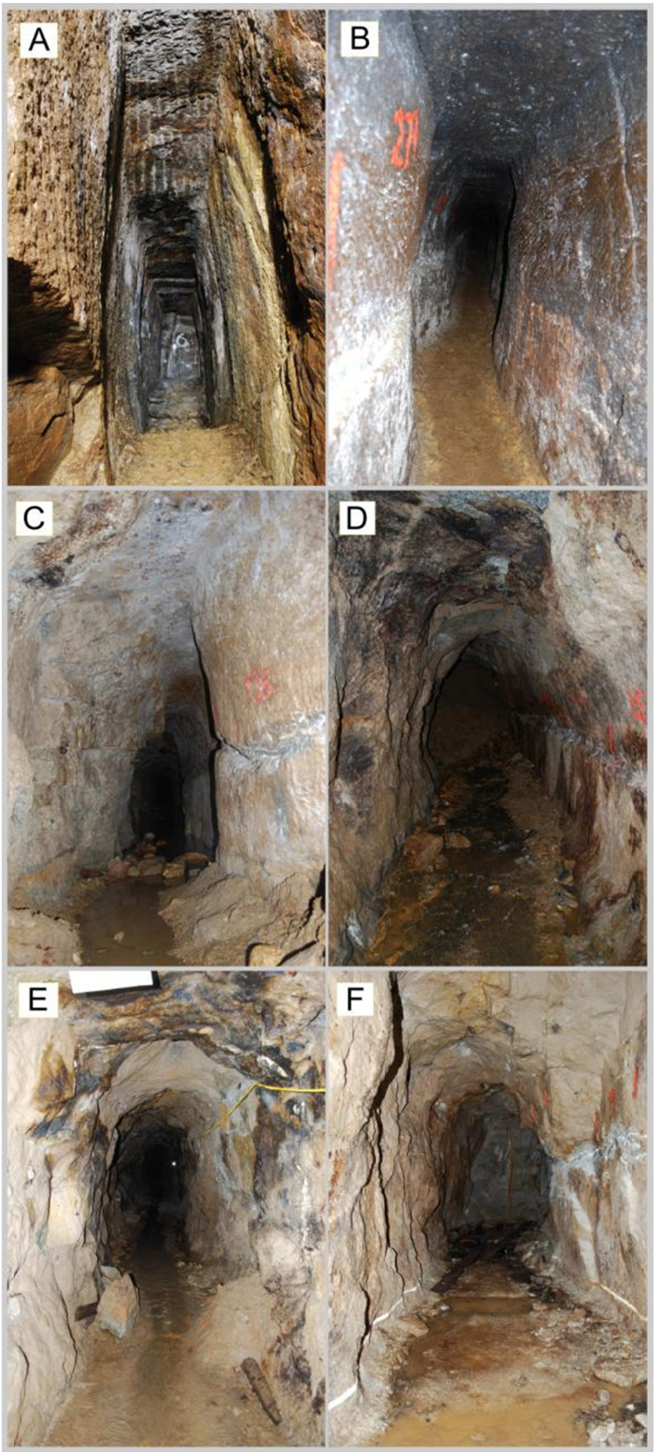

Fig. 5. Examples of galleries in the Jeroným Mine (*photo:* Lednická): (a,b) space-saving profile made by hand tools, height 1.5 m; (c,d) handmade profile expanded by blasting operations, height 2 m; (e,f) gallery driven by blasting operations, height 2 m

Galleries, made by blasting, have a typical flaking-off phenomena, caused mainly by ongoing weathering processes in a cracked zone.

Used mining methods have had an influence on cracking of rock massif, radius of cracked zone and consequently on weathering processes in surface layers at these places. Granite may weather away by chemical decomposition or by physical disintegration; however, in most cases these processes act together. During chemical decomposition of granites, feldspars are decomposed to various clay minerals. The rock disintegrates mechanically by opening the fissures and forming new discontinuities. The type and grade of weathering depends on climatic conditions, namely, on temperature and precipitation (Bell, 2004). Chemical weathering processes mostly prevail in wet environments. Presence of water accelerates weathering process, not only because water itself is an efficient weathering agent, but, in addition, it may contain dissolved substances that react with component minerals of rock. Chemical weathering processes may be further accelerated by mechanical breakdown that leads to the enlargement of mineral surfaces.

Weathering in the Jeroným Mine takes its course by both physical disintegration and chemical decomposition. Such specific climatic conditions like a relatively constant temperature of 4-8 degrees Celsius, almost a hundred per cent humidity, and minimum air movement prevail. Under these conditions, it is possible to eliminate some types of physical weathering processes, e.g. mechanical weathering owing to frost wedging or thermal expansion, and also owing to changes of temperature in the daytime and at night. Conversely, the anthropogenic activity connected with mining caused mechanical breakdown of the massif, i.e. opening up already existing fissures or forming new ones. Biological weathering in underground spaces of the Jeroným Mine, localized close to the surface, is also observable. It concerns the chambers with sinking roofs into which caved material leads from the surface. It is possible to see roots of trees penetrating into the caved material and into cracks in the roofs.

In previous studies (Lednická & Kaláb, 2012; Lednická & Kaláb, 2013b), results of initial measurements of UPV (*ultrasonic pulse velocity*) and R (*Schmidt hammer rebound value*) for different weathering grades are presented and the summary of results is given in Table 1. Determination of weathering grade of rock massif in selected places of the mine was carried out visually. It means that colour changes of rock massif, presence of cracks visible on the surface, friability, and visual assessment of weathering state of feldspars were evaluated. The classification of granites, presented by Hencher and Martin (in Vahed et al., 2009), has been selected for the determination of weathering grade for our study (see Table 2).

TABLE 1

Initial measurements of UPV and R values for different weathering grades of granite rock massif in the Jeroným mine (according Lednická & Kaláb, 2012; Lednická & Kaláb, 2013b)

Grade	Description	UPV, [m/s]	R, [-]
I	Fresh rock	–	–
I-II	Fresh to slightly weathered rock	4600-5300	44-51
II	Slightly weathered rock	4200-4600	35-44
II-III	Slightly to moderately weathered rock	3400-4200	28-35
III	Moderately weathered rock	3000-3400	20-28
IV	Highly weathered rock	2700-3000	12-20
V	Completely weathered rock	2500-2700	No value
VI	Residual soil	No value	No value

TABLE 2

Weathering classification system for granite and volcanic rocks presented by Hencher and Martin (in Vahed et al., 2009)

Grade	Description	Typical Distinctive Characteristic
I	Fresh rock	No visible signs of weathering or discolored
II	Slightly weathered rock	Discolored along discontinuities; Strength approaches that of fresh rock; N Schmidt rebound value greater than 45; More than one blow of geological hammer to break specimen
III	Moderately weathered rock	Completely discolored; Considerably weathered but possessing strength such that pieces 55 mm diameter cannot be broken by hand; N Schmidt rebound value of 25 to 45; Rock material not friable
IV	Highly weathered rock	Rock weakened so that large pieces can be broken by hand; Positive N Schmidt rebound value up to 25; Does not slake readily in water; Geological pick cannot be pushed into surface; Hand penetrometer strength index greater than 250 kPa; Individual grain may be plucked from surface
V	Completely weathered rock	Rock wholly weathered but rock texture preserved; No rebound from N Schmidt hammer; Slake readily in water; Geological pick easily indents surface when pushed
VI	Residual soil	A soil formed by weathering in place but with original texture of rock completely destroyed

4. Non-destructive testing methods used in the locality

4.1. Ultrasonic pulse velocity measurement

In laboratory conditions, it is possible to perform precise UPV measurements on specimens under defined conditions. Laboratory UPV measurements of granites with various weathering grades were implemented by a number of authors, e.g. (Vasconcelos et al., 2008; Gupta & Rao, 1998). The UPV can be correlated with a number of rock parameters, such as density, porosity, humidity, strength, Young modulus, etc. However, it is impossible to make exact ultrasonic measurements in field conditions of the mine. Ultrasonic measurements in the Jeroným Mine were performed by portable ultrasonic apparatus. Geometry of workings only allows to use indirect measurement on the walls and roof of workings. Direct measurements may be used only through thin pillars.

Some recommendations resulted from initial non-destructive measurements performed in the Jeroným Mine and they were mentioned in the paper (Lednická & Kaláb, 2012). Among others, it was found out that plasticine was the only acoustic couplant that made the measurement possible on rough surface of rock massif. The correct transmission time was possible to determine only from waveform records of ultrasonic signal.

4.2. Measurement of Schmidt hammer rebound value

The Schmidt hammer is widely used for approximate determination of surface hardness of concrete, but this method is also widespread when investigating properties of rock massif (Viles et al., 2011). The height of rebound of a piston, indicated on the scale of rebound hammer, correlates to the surface hardness of material. The N-type Schmidt hammer with impact energy of the spring of 2.207 Nm was used in our measurements. The rebound values are influenced by gravitational forces so that non-horizontal values must be normalized with reference to the horizontal direction. Apart from surface hardness, the rebound value of Schmidt hammer depends on the relative strength of coarse grains versus matrix, moisture content, anisotropy, etc, (Aydin, 2009). During the field measurements in the Jeroným Mine, such effects were not proved in detail.

5. Experimental measurement in selected galleries

Experimental measurement was performed in two different galleries situated at the lowest accessible level of the mine (Fig. 1). Both galleries were made by hand tools probably in the 17th or 18th century and they were partly extended later by blasting operations. Two different mining methods, used in the same gallery, enabled to study how each used method influences the extent of cracked zone and weathering of surface layers of rock massif.

In Fig. 6 there are profiles of selected galleries with numbering of measured sections. The profile A is situated in the gallery located in the depth of 50 m below the surface near the Jeroným shaft. This gallery was presumably re-discovered during World War II and extended by blasting operations at that time. The handmade profile covers sections of measurement from 1 to 10; extended part of the profile is from 11 to 21. The second studied gallery was also extended from the original handmade profile, either during World War II or during the 19th century. The handmade profile is from the section 1 to 6 so this gallery was apparently only 1.5 m high. There is weathered material and small blocks of rock massif at the bottom of both galleries, partly probably flaked-off from the walls and roof, partly flushed away by water. According to the visual assessment, weathering grade of rock massif in the profile B seems to be higher than that in the profile A. The walls of the profile B show considerable colour changes in both handmade and extended part. The surface layer of rock massif is completely weathered around the section no. 10.

The ultrasonic portable apparatus Pundit Lab (Proceq Company) was used for presented UPV measurement. The measurement was performed with transducers of frequency of 150 kHz and plasticine was used as an acoustic couplant. The indirect measurement in the profile A was made on 21 sections (Fig. 6). The distance of transmitting and receiving transducers was at each section 0.2 m and 0.4 m. Selected distance of transducers is sufficient for the frequency of 150 kHz according to the producer´s recommendation. 10 values of transmission time were recorded in each measured section together with wave patterns for both distances of transducers. After the measurement, detailed interpretation of recorded wave patterns was performed by Punditlink software and corrected transmission times were used for calculation of UPV. In the profile A, the wave pattern was of a good quality for almost all measured places (except for three sections in extended part of the profile – no. 13, 19 and 21).

The measurement in the profile B was taken in 22 sections (Fig. 6) with distances of transducers of 0.2 and 0.3 m. Compared to the profile A, the measurement in the profile B showed a quick attenuation of ultrasonic pulse and that is why the used distance of transducers was only up to 0.3 m. In the extended part of the profile, only a half of measured places have an interpretable wave pattern.

The measurement of R values using the N-type Schmidt hammer was performed in the same profiles A and B. The size of measured areas varied from 30 × 10 cm to 30 × 20 cm and it corresponded to the sections where UPV measurement was accomplished. The measurements were carried out on 10 points uniformly distributed across the measured area. Measured R values were corrected according to the hammer position.

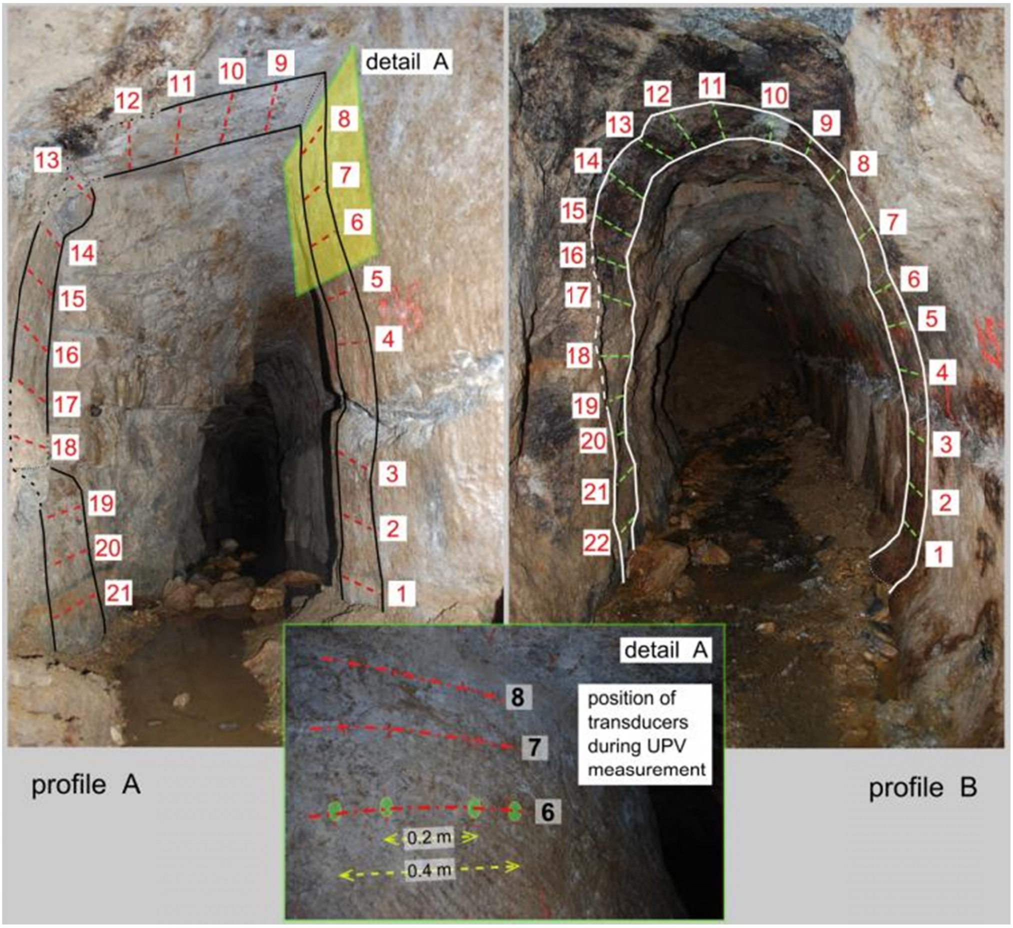

Fig. 6. Sketch of selected profiles of galleries and numbering of measured sections

6. Results and discussion

The data sets of UPV and R values measured in each section were elaborated using box-whisker plots and the results are shown in Fig. 7 and 8. Calculated median values of UPV and R were used for presentation of results in the Fig. 9.

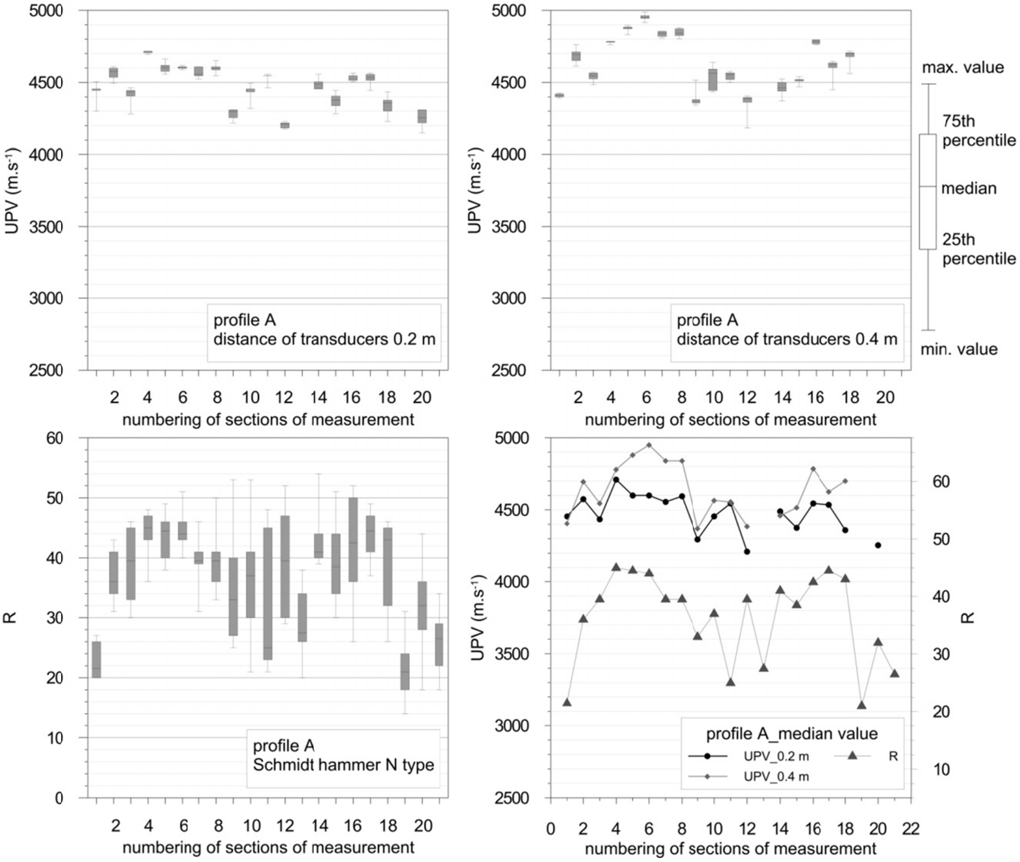

Fig. 7. UPV and R values measured in the individual sections of profile A.

UPV for the profile A ranges from 4200 m/s to 4700 m/s (transducer distance 0.2 m) and from 4300 m/s to 5000 m/s (transducer distance 0.4 m). In comparison with Table 1, it corresponds to slightly weathered rock massif, rarely almost fresh rock massif. There is a considerable difference in UPV for two different distances of transducers in the profile sections from 5 to 8. In this place, rock massif shows lower weathering grade in the deeper layer below the surface (almost fresh rock). This difference may also be caused by existing layer with different rock massif parameters, e.g. layer with higher amount of quartz. In the profile sections 13, 19, 20 and 21 the UPV values were not possible to determine, only for the section no. 20 with the transducer distance of 0.2 m. In these parts of profile, it is probably the rest of cracked zone around the profile extended by blasting. In the sections from 14 to18 the cracked zone of rock massif probably flaked-off in the past and that is why the UPV is higher and corresponds to slightly weathered and/or almost fresh rock massif outside the cracked zone.

R values were measured in all sections of the profile A. The results of R values are not as clear as UPV values, because of great range of measured values, especially on the roof of a gallery (sections from 9 to 12). The highest R values correspond to the highest values of UPV, in the sections 4, 5, 6 and 16. In these places median values range from 43 to 45 and it also matches slightly weathered rock massif, infrequently almost fresh rock massif. The lowest values accord with sections where no UPV were determined (13, 19, 20 and 21). The lower R value was also measured in the point 1 – R value is equal to 22 and it corresponds to moderately weathered rock massif. It may be caused by chemical weathering processes in the surface layer of rock massif at this place, because this part of rock massif was flooded in the past.

Measured values of UPV for the profile B are in wide range from 2900 m/s to 4350 m/s. It corresponds to a moderately and slightly weathered rock massif. Clear results for UPV can be seen at the beginning of the profile where is handmade zone (sections from 1 to 6). There are no differences in UPV for two different distances of transducer, so the rock massif is of the same quality to the depth of approximately 0.1 m. The UPV values were not determined in the sections of the profile from 8 to 11; the rock massif was highly weathered on the roof of a gallery. The rest part of the profile, extended by blasting, has the values different for each section and the data set in each section are of wide range. Cracks in the rock massif cause the attenuation of ultrasonic pulse and at the same time a very bad quality of UPV measurement. It these parts, it is probably the rest of cracked zone around the profile extended by blasting.

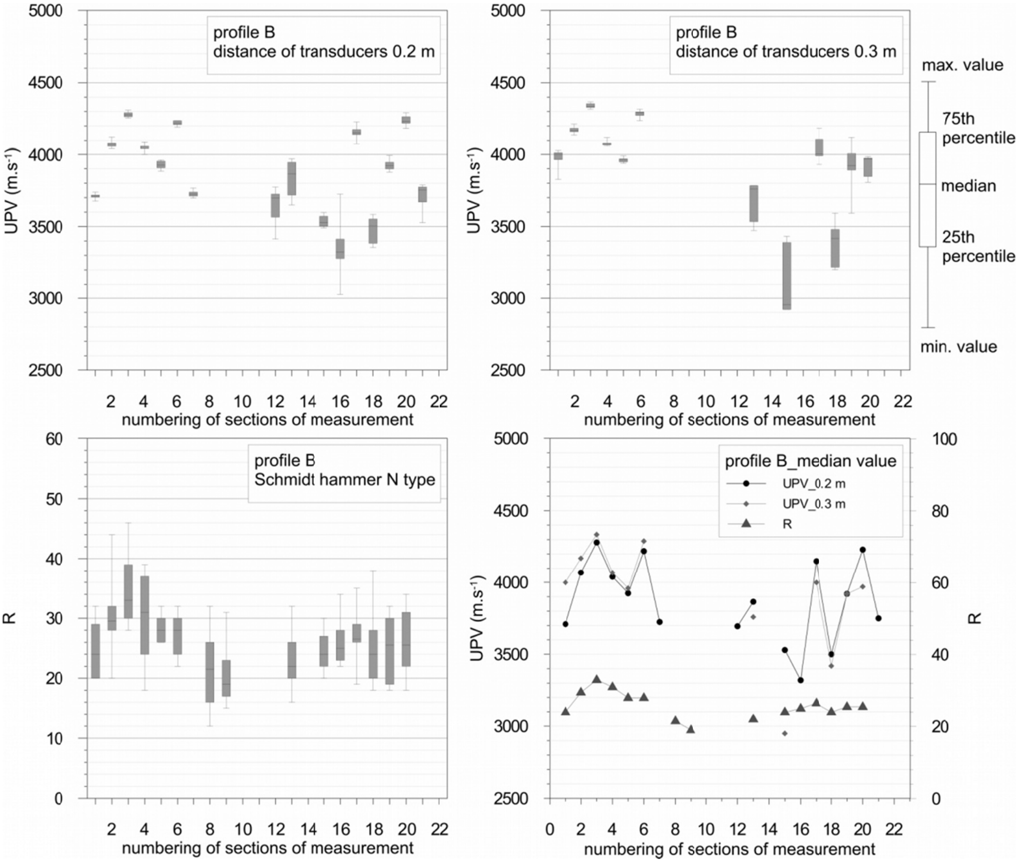

Fig. 8. UPV and R values measured in the individual sections of profile B

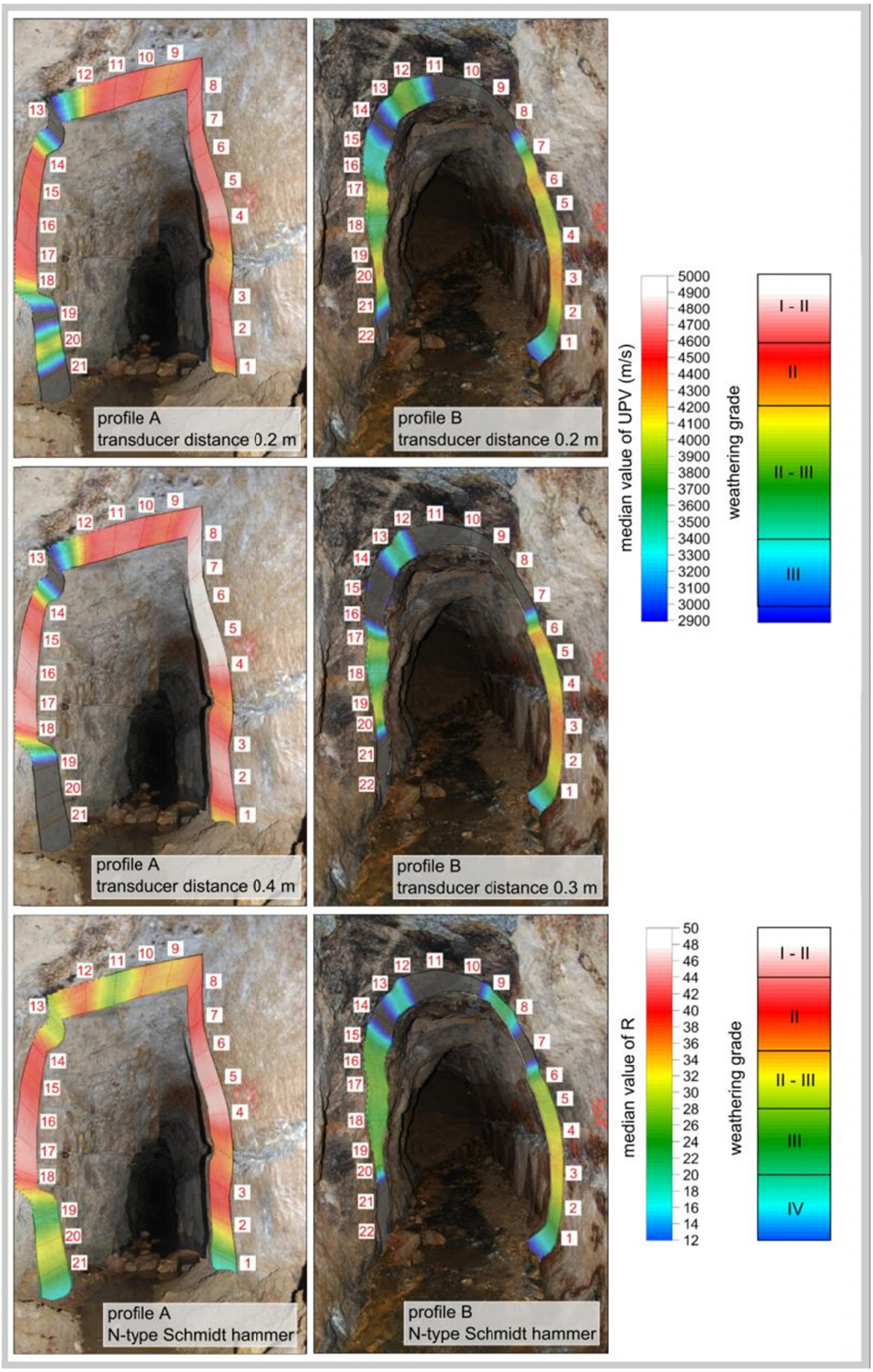

Fig. 9. Illustration of calculated median values of UPV and R and corresponding weathering grade in the profiles A and B

The results of R values range from 19 to 34 which also correspond to a moderately and slightly weathered rock massif. Values were not determined on the roof of a gallery where the rock massif is highly and/or completely weathered. At the beginning of the profile, the R values correspond to UPV values, but for an extended part of the profile it is not possible to compare these values. The R values are quite stable for sections from 15 to 20, but not values of UPV. The reason is probably that the cracked zone is formed by the blocks of a moderately weathered massif and it is possible to measure rebound values at these places. But due to some cracks ultrasonic pulse is quickly attenuated in the rock massif and the wave pattern is of a bad quality. It is not possible to determine transmission time and calculate UPV values.

7. Conclusions

This paper presents the application of two selected non-destructive testing methods for characterization of weathering in the historical parts of the medieval mine. According to the results obtained from the in situ measurements, it is possible to state that measurements of UPV and R values are applicable as supplementary methods evaluating the weathering grade of rock massif in this mine. Referring to these results the weathering grade of the rock massif and/or cracking of surface layers may be defined and a suitable type of underground spaces stabilization may be selected. The most valuable historical parts have to be certainly preserved in their original state.

According to the results, it is possible to say that the oldest and the most valuable mine workings, made by hand tools, show only a negligible formation of cracks in a surface layer of the rock massif. Generally, only chemical weathering took part in the surface layers of the handmade profiles, and the weathering grade depends mainly on the underground climatic conditions such as the presence of water movement and air moisture content. In almost all places, these handmade profiles have been preserved in original state and flaking-off phenomena have seldom been found there. In two investigated galleries, handmade parts of profile show from a moderately to slightly weathered rock massif without cracks, and almost fresh rock massif was documented in some places. On the other hand, blasting operations, used since 19th century, cause higher deterioration of surface layers of the rock massif around galleries. In these cracked zones weathering processes take its course more quickly and they cause flaking-off of surface layers of rock massif there. The UPV and R values were not determined on the gallery roof of the profile B where the rock massif was highly to completely weathered and consequently the flaking-off phenomena may occur at this place. Information about possible flaking-off phenomena is very important for safety of people attending underground spaces and also for assessing the stability of these places and for subsequent stabilization of the most hazardous parts.

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