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EVALUATION OF ROCK MASS QUALITY IN MEDIEVAL MINE USING SCHMIDT HAMMER REBOUND HARDNESS

HODNOCENÍ KVALITY HORNINOVÉHO MASIVU VE STŘEDOVĚKÉM DOLE PODLE ODRAZOVÉ TVRDOSTI MĚŘENÉ SCHMIDTOVÝM KLADÍVKEM

Markéta Lednická [1]

Abstract

This paper presents results of non-destructive testing of rock mass quality in the Jeroným Mine that is one of the most preserved examples of medieval mining in the central Europe. In such a historical monument, all of works have to be realized non-destructively. The Schmidt hammer rebound testing presented in this paper is one of possibilities how to investigate rock mass quality without visual damage. Almost all parts of underground spaces are mined out in granitic rocks and it is possible to document all of weathering grades of the granite rock mass at the locality. Two types of hammers were used for in situ testing and both types were found to be suitable for the rock mass characterization at the locality. In addition, rebound values were compared to results of other non-destructive method, namely the ultrasonic pulse velocities. Good correlation between both parameters proved that results of both methods are comparable for purposes of the rock mass quality evaluation.

Abstrakt

V příspěvku jsou popsány výsledky nedestruktivního zkoumání kvality horninového masivu v Dole Jeroným, který představuje jeden z nejlépe dochovaných příkladů středověkého hornictví ve střední Evropě. V případě takovéto historické památky je třeba přistupovat k veškerým pracím nedestruktivním způsobem. Testování odrazové tvrdosti pomocí Schmidtova kladívka je jednou z možností jak zkoumat kvalitu horninového masivu bez viditelného poškození. Téměř všechny části podzemních prostor jsou vyraženy v granitických horninách a na lokalitě lze nalézt všechny stupně zvětrání těchto hornin. Pro terénní měření byly použity dva typy kladívek a oba dva typy se ukázaly být vhodnými pro charakterizaci horninového masivu na dané lokalitě. Hodnoty odrazové tvrdosti byly navíc porovnány s výsledky jiné

nedestruktivní metody, a to s rychlostmi šíření ultrazvukových vln. Dobrá korelace mezi těmito parametry prokázala, že výsledky obou metod jsou srovnatelné ve smyslu hodnocení kvality horninového masivu.

Key words

Schmidt hammer, rebound hardness, granite, weathering, non-destructive testing

Klíčová slova

Schmidtovo kladívko, odrazová tvrdost, granit, zvětrávání, nedestruktivní testování

1 Introduction

Non-destructive testing of rock materials is often used as a tool to characterise rock mass quality and its degradation or a tool to obtain the information on selected properties without rock material destruction. Non-destructive testing methods are used both in situ to characterise rock mass in the field and in laboratory conditions for testing of rock samples. Parameters determined by non-destructive testing often relate to the properties of rocks, e.g. Schmidt hammer rebound hardness (R) versus density, porosity, compressive strength, tensile strength, Young´s modulus (Aydin and Basu, 2005; Bilgin et al., 2016; Buyuksagis and Goktan, 2007; Mishra and Basu, 2013; Tumac, 2015; Vasconcelos et al., 2008); ultrasonic pulse velocity (UPV) versus density, porosity, compressive strength, tensile strength, Young´s modulus (Begonha and Sequeira Braga, 2002; Nováková et al., 2011; Vasconcelos et al., 2008); drilling resistance versus density, porosity, compressive strength, Young´s modulus (Theodoridou et al., 2015). Non-destructive testing is very important at localities where no damage of rock material is required, such as historical monuments, works of arts, surfaces of constructions, etc. The medieval Jeroným Mine presented in this paper is such a case of historical monument where majority of works have to be realized non-destructively. This shallow underground mine represents mining history since 15th century with valuable traces of medieval mining methods as fire settings and traces of work with a hammer and a pick (Tomíček, 2016; Žůrek and Kořínek, 2001/2002). Almost whole underground complex is mined out in granitic rocks and all of weathering grades of the granite rock is possible to document at the locality, from almost fresh rock up to completely weathered rock and residual soil in collapsed parts. Knowledge in rock mass quality is important for stability assessment and to find the most suitable stabilizing and treatment methods to preserve the most valuable parts of the mine in original state. Information obtained based on non-destructive in-situ testing supplements results of the monitoring performed in the mine as e.g. monitoring of mine water level changes, seismic monitoring, radon activity concentration monitoring, detection of movement along the discontinuities and cracks, convergence measurement (Froňka et al., 2013; Kaláb et al., 2008; Kaláb et al., 2015; Kaláb and Lednická, 2016; Knejzlík et al., 2011; Lednická et al., 2012; Lednická and Kaláb, 2013a; Telesca et al., 2011). Monitoring of these parameters is first of all of importance due to health protection of people attending these spaces as workers or visitors. Part of the Jeroným Mine is opened to public since 2013 and its popularity increases among tourists, specialists in mining history, scientists and others.

Different non-destructive and semi-destructive methods were already tested at the locality of the Jeroným Mine (Lednická and Kaláb, 2013b) – e.g. UPV measurement using Pundit lab equipment (Proceq, Switzerland), drilling resistance measurement using DRMS cordless

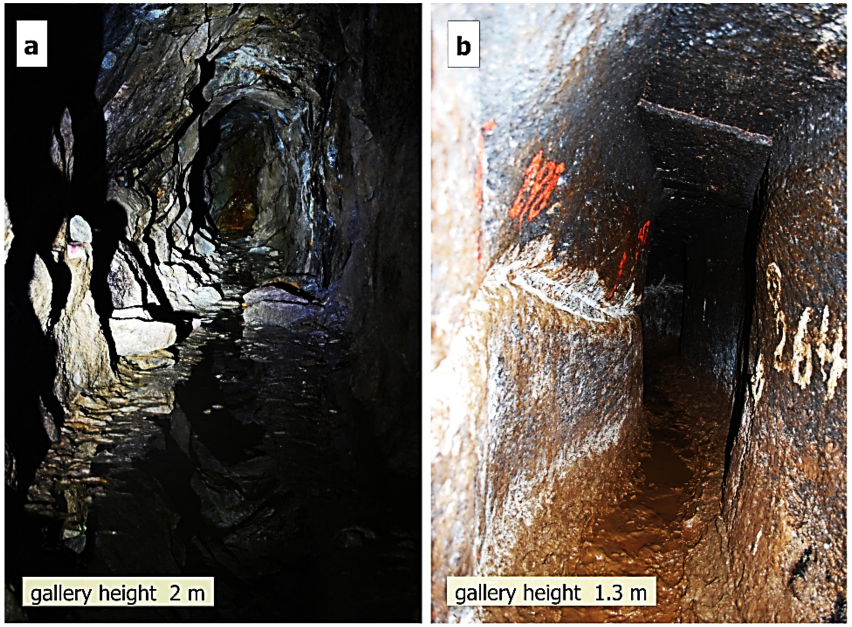

***Fig. 1** Examples of galleries mined out by different methods–by blasting operations (a) and by hand tools as a picker and a hammer (b)*

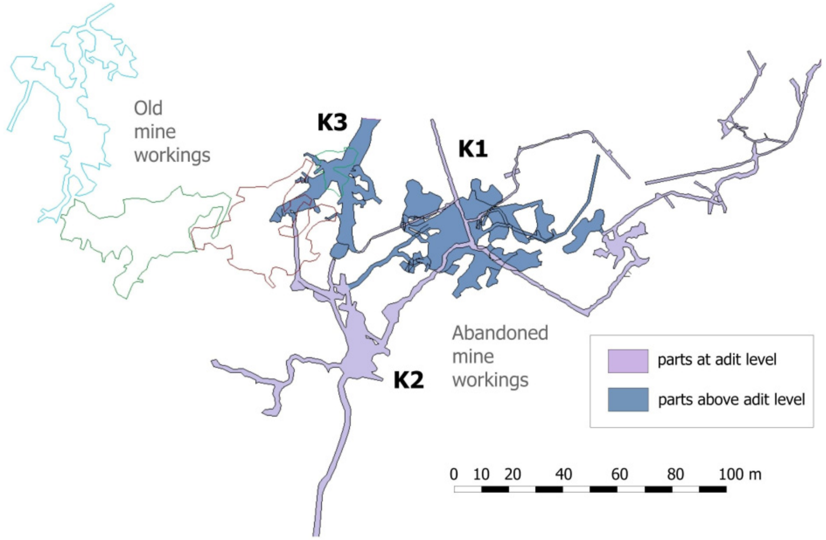

***Fig. 2** System of mine workings at the locality of the Jeroným Mine; K1, K2 and K3 are the largest chambers in the part called "Abandoned mine workings"*

system (Sint Technology, Italy) and also Schmidt hammer rebound testing. The last mentioned method is widely used in material characterization, mostly in concretes and rocks (Aydin, 2009; Szilágyi et al., 2014; Vavro et al., 2015). But its popularity increases also among geomorphologists and heritage scientists, especially due to its applicability, easy use and low costs (Ericson, 2004; Fort et al., 2013; Kłapyta, 2013; Viles et al., 2011). The Schmidt hammer consists of a spring-loaded piston. When the hammer is pressed against a surface, the piston is automatically released onto the plunger and the rebound height of the piston is considered to be an index of surface hardness (Basu and Aydin, 2004). Based on previous studies performed in the Jeroným Mine, the Schmidt hammer rebound testing seems to be simpler and less time-consuming method compared to measurement of UPV and drilling resistance.

In the presented article, results of the Schmidt hammer rebound testing are summarized that were measured in different parts of the Jeroným Mine comprising all weathering grades of the granite rock. Two types of hammers were used and two different methods of the rebound value measurement were applied. Obtained results were analysed considering mining method used at measured places. In addition, the rebound values were correlated to the results of UPV measurement to see how results of these two non-destructive methods are comparable regarding the weathering grade determination.

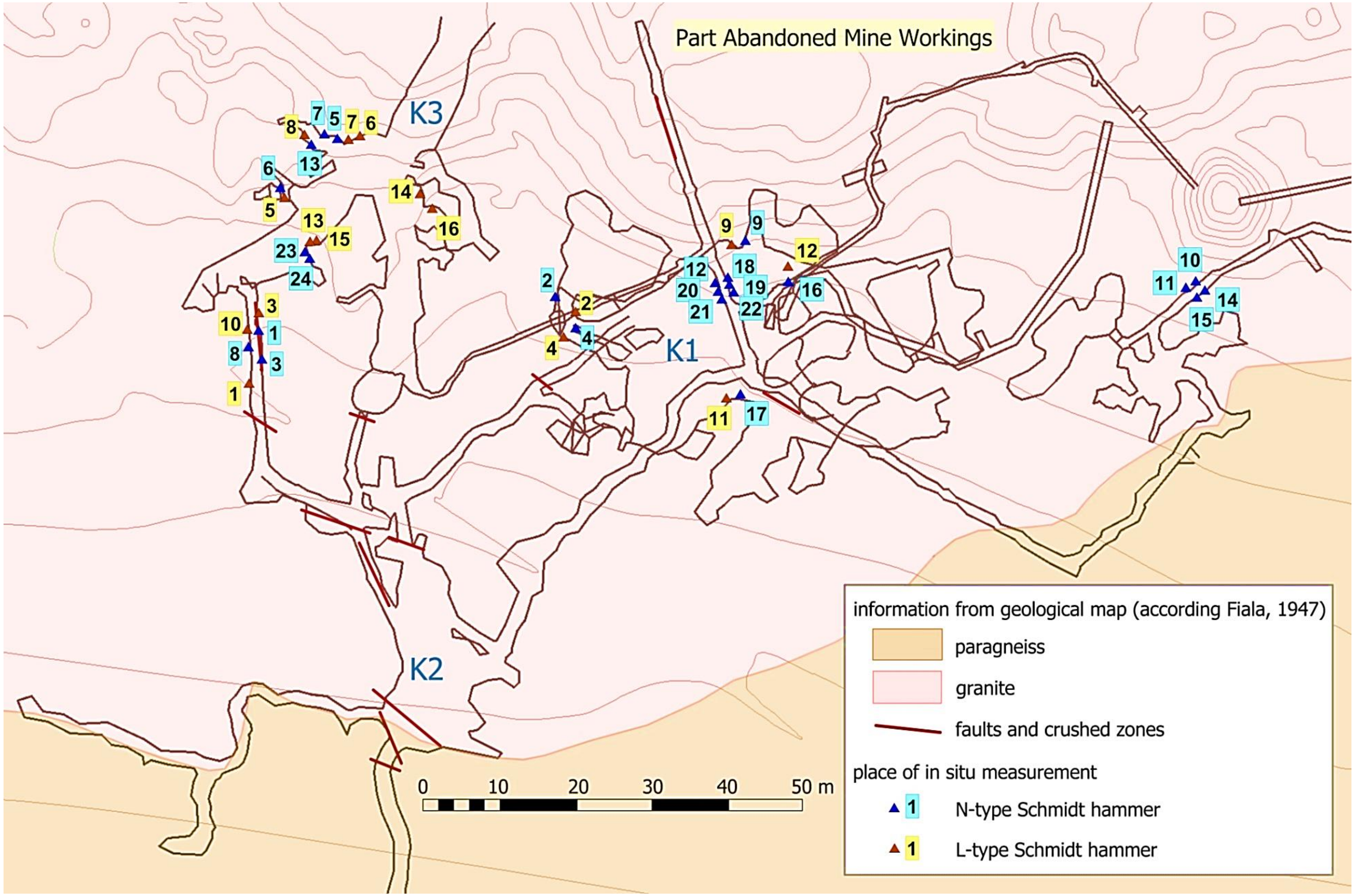

Fig.3 Geological situation at the locality (according geological map compiled by Fiala, 1947) and position of measured places

2 Description of locality

The Jeroným Mine represents valuable example of medieval mining of tin deposits, one of the most preserved in the central Europe (Tomíček, 2016; Žůrek and Kořínek, 2001/2002). At this time, part of the mine is opened to public and unknown parts are discovered up to now, that were inaccessible for several hundreds of years. The Jeroným Mine is located near the former "Čistá" municipality (also known as Lauterbach Stadt) and is a part of protected landscape area, the Slavkovský Les Mountains (Raška and Kirchner, 2011). At present, the Jeroným Mine is included in the Egeria National Geo-park (www.geopark.cz) as one of the most valuable locality.

The Jeroným Mine consists of an underground system of large chambers at different levels that are connected by the system of several galleries and shafts. The lowest level at the depth below 50 m under the surface is permanently flooded and its scope is unknown. From the geological viewpoint the territory consists of metamorphosed rocks of the Slavkov mantle crystalline complex (primarily the biotite paragneisses that are migmatitized in various intensities and granitized upon intrusion of granites) and of Variscian granites of the Ore Mountains pluton. Weathering of the granite rock mass in the Jeroným Mine takes its course by physical disintegration and chemical decomposition (Bell, 2000). During the chemical decomposition, feldspars are decomposed to various clay minerals. Mechanically, the rock disintegrates by opening the fissures and forming new discontinuities. The intensity and scale of discontinuities often grows with the extent of weathering and the chemical weathering processes may be further accelerated by mechanical breakdown that leads to the enlargement of mineral surfaces.

The weathering at the Jeroným Mine is connected among others with used mining method, as was presented in previous study (Lednická and Kaláb, 2016). It was documented in investigated places of hand mined and blasting driven galleries, that the oldest handmade parts show only a negligible formation of cracks in a surface layer of the rock mass. 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, the handmade profiles have been preserved in original state and flaking-off phenomena have seldom been found there. On the other hand, blasting operations used at the locality caused higher deterioration of surface layers of the rock mass. During blasting, cracked zone is induced around blast hole and its depth depends on e.g. quasi-static pressure on the wall of the hole, tensile strength of rock, radius of the hole, detonator charge radius, detonation velocity and rock density (Li et al., 2009). In these cracked zones weathering processes take its course more quickly and they cause flaking-off of surface layers of such driven mine workings. Examples of galleries driven by blasting operations and by hand tools are presented on the fig.1. The highest rock mass quality with the minimum traces of weathering processes was documented at the planes, where rock blocks were separated along the discontinuities or planes of cleavage. Structural geology and fault zones are other important parameters that should be taken into account when assessing rock mass quality and ongoing weathering processes considering the results of non-destructive testing. Unfortunately, no detailed structural geological maps are elaborated for the Jeroným Mine. Only one historical geological map compiled by Fiala (1947) is available for the part of the mine complex.

Non-destructive testing using the Schmidt hammer was realized on all types of surfaces – made by hand tools, driven by blasting operations and at planes of cleavage. All of presented measurements were realized in the part of mine complex called Abandoned mine workings (AMW, see fig.2), namely in two largest chambers signed as K1 and K3 and in the galleries at the adit level. Detailed information about position of measured places is presented in the map on the fig.3 together with geological situation at the locality (according Fiala, 1947).

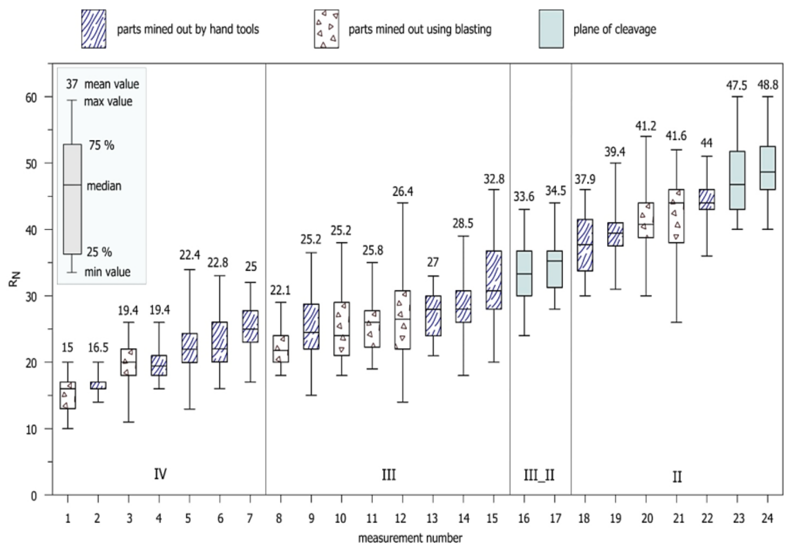

Fig.5 Results of N-type Schmidt hammer rebound hardness depending on the weathering grade

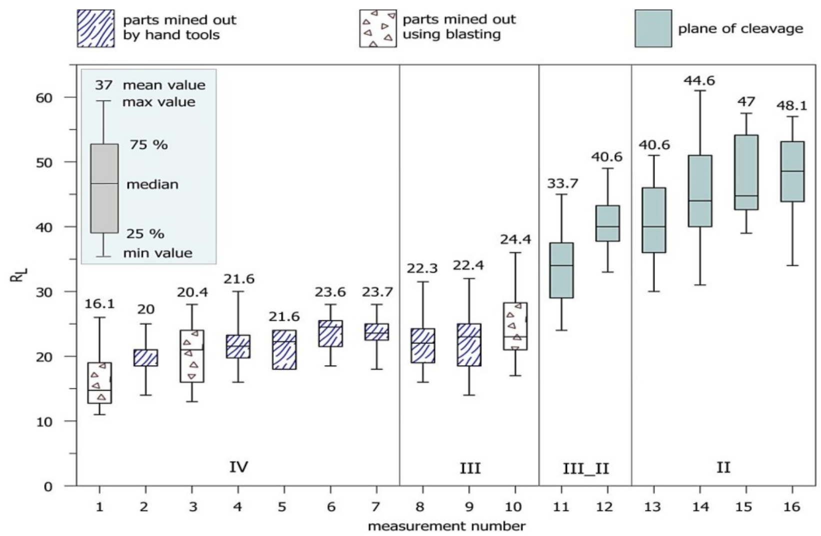

Fig.6 Results of L-type Schmidt hammer rebound hardness depending on the weathering grade

Fig. 4 The L-type Schmidt hammer (Proceq, Switzerland)

3 Measurement and methods

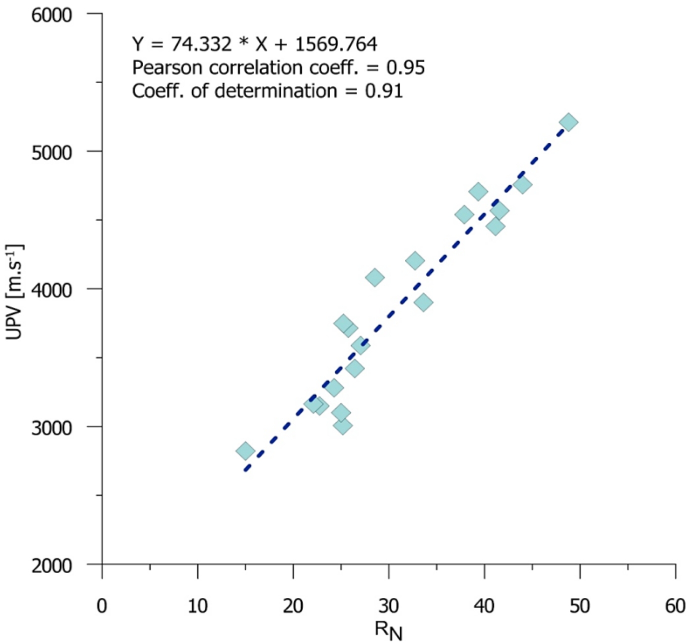

Fig. 7 Correlation between the mean values of UPV and R_N measured at the same planes

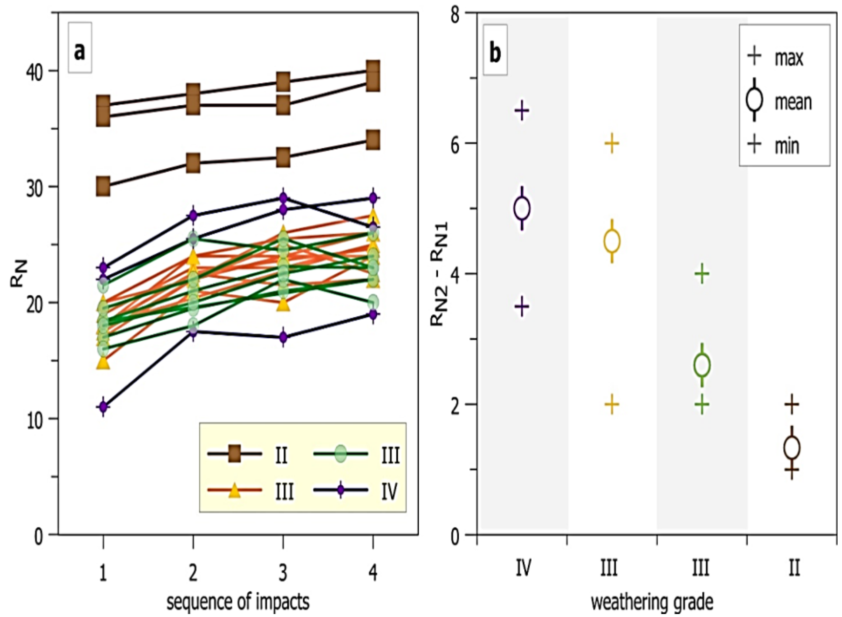

Fig.8 Results of multiple impacts of N-type Schmidt hammer measured on four different planes with reference to the weathering grade. The R_N values of four consecutive impacts for investigated planes (a) and for maximum, minimum and mean value of R_N difference for investigated planes (b). R_{N1}–R_{N2} is the difference between the second and the first impact at the given point.

Two types of the Schmidt hammer were used for testing at the locality, N-type and L-type, whose impact energies are 2.207 and 0.735 Nm, respectively, example in the fig.4. Measurements of the Schmidt hammer rebound hardness R were realized in several parts of the mine–on the walls of large and small chambers, on the pillars and on the walls of galleries. Measured planes were selected so that all of the weathering grades could be investigated. The measurements of R values were carried out on 20 points uniformly distributed across the measured plane of the size approximately 30 × 30 cm. The R values are influenced by gravitational forces so that non-horizontal values were normalized with reference to the horizontal direction. The weathering grade of individual places was evaluated visually according the classification presented by Hencher and Martin (in Vahed et al., 2009) used for granite rocks; tab.1. At the tested parts, colour changes of the rock mass, presence of cracks visible on the surface, friability and visual assessment of the weathering state of feldspars were evaluated. Short description of the tested planes and the resulting R values (minimum, maximum and mean) are presented in the tab.2 and tab.3 for

N-type and L-type hammer, respectively. At several parts where N-type hammer rebound hardness R_N has been measured, ultrasonic testing has been also realized. The results of UPV (minimum, maximum and mean) are presented in the tab.2 and they are used for estimating correlation of UPV vs. R_N. In the study by Basu et al. (2009), authors proved that changes in R values due to multiple impacts at one representative test point are more efficient in predicting weathering grades than conventional averaged single impact R values. This testing method was used also at four selected places in the Jeroným Mine. Four consecutive impacts were performed at each of the chosen points and differences of R values between the second and the first impact were evaluated for the individual weathering grades.

4 Results

Results of measurements are presented in the tab.2 and 3 and on the fig.5 and 6 using box-whisker plots. The weathering grades of investigated rock mass ranged from slightly to completely weathered rock. Nevertheless, results are displayed only for the weathering grade ranging from slightly to highly weathered rock. For the completely weathered rock investigated in galleries driven by blasting, no R values were obtained; only UPV values were determined in the range from 2500 to 2700 $m.s^{-1}$. During the field rock mass investigation with using N-type and L-type hammer, measurements were carried out at different places, so the results presented in tab.2 and 3 are not used for estimating the correlation between obtained R_N and R_L values. Nevertheless similar trend is possible to see from the fig.5 and 6 for R_L and R_N values depending on the individual weathering grade. If we look at the mining method used, parts made by hand tools are characterized by the range of weathering grade from II to IV. The parts driven by blasting operations are characterized mainly by the weathering grades from III to V (with no R values obtained for the weathering grade V); except for two cases of the weathering grade II (tab.2; measurement number 20 and 21). These two places were investigated in the gallery, where old handmade profile has been extended during the Second World War by blasting. Places of these two measurements correspond to slightly weathered rock outside the cracked zone of the wall that probably flaked off in the past (Lednická and Kaláb, 2016). Almost fresh rock has been usually found on the planes of cleavage where no cracks occur and colour changes are documented only occasionally. Although there is no available information about structural pattern for all of measured places, it is apparent from the fig.3 that the measured points no. 1 and 3 (N-type hammer) and no. 3 (L-type hammer) of highly weathered rock are located in the part where fault and/or crushed zone is documented by Fiala (1947). In addition, completely weathered rock with no R values has been documented at this part also. These results confirmed necessity of structural pattern consideration in next studies at the locality when evaluating the rock mass quality.

Mean values of R_N and UPV presented in the tab.2 were used for estimating relation between these two non-destructively obtained parameters. The UPV plotted against the R_N shows a good linear correlation (fig.7) with Pearson correlation coefficient equal to 0.95. This finding confirms that both of these parameters determined by non-destructive testing give us useful information about the rock mass quality and the weathering grade and that results of these two methods are comparable.

Results of multiple impacts measured at one point are presented on the fig.8. The R_N values of four consecutive impacts are plotted for all points measured at four selected planes. The weathering grade of these planes ranges from II to IV and measurements at individual planes are distinguished using different colours. The highest increase in the R_N is obvious between the second and the first value in almost all cases. Range of measured R_N values is quite wide and it overlaps within the weathering grade III and IV (fig.8a) as well as range of R_N difference between the second and the first impact (fig.8b). Nevertheless it is possible to see decreasing trend of the mean value of R_N difference with decreasing weathering grade.

Tab.1 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 of discoloured
II	Slightly weathered rock	Discoloured 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 discoloured
		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

Tab.2 Results of N-type Schmidt hammer rebound hardness R_N and ultrasonic pulse velocity UPV measured at investigated parts of rock mass in the Jeroným Mine

Measur. number	Weathering grade	R_N min–max; mean	UPV [$m.s^{-1}$] min–max; mean	Description of measured place
1	IV	10–20; 15	2375–3095; 2821	Wall of the gallery driven by blasting operations
2	IV	14–20; 16.5		Wall of the chamber made by hand tools
3	IV	11–26; 19.4		Wall of the gallery driven by blasting operations
4	IV	16–26; 19.4		Wall of the chamber made by hand tools
5	IV	13–34; 22.4		Wall of the chamber made by hand tools
6	IV	16–33; 22.8	2721–3351; 3150	Wall of the chamber made by hand tools
7	IV	17–32; 25	2061–3492; 3101	Wall of the chamber made by hand tools
8	III	18–29; 22.1	2829–3553; 3163	Wall of the gallery driven by blasting operations
9	III	15–36.5; 25.2	2610–3248; 3007	Wall of the chamber made by hand tools
10	III	18–38; 25.2	3208–4172; 3748	Wall of the gallery driven by blasting operations
11	III	19–35; 25.8	2912–4219; 3715	Wall of the gallery driven by blasting operations
12	III	14–44; 26.4	1063–4914; 3422	Wall of the gallery driven by blasting operations
13	III	21–33; 27	3333–3689; 3588	Wall of the chamber made by hand tools
14	III	18–39; 28.5	3883–4304; 4081	Wall of the gallery made by hand tools
15	III	20–46; 32.8	4040–4360; 4203	Wall of the gallery made by hand tools
16	II–III	24–43; 33.6	3448–4545; 3900	Plane of cleavage, wall of large chamber
17	II–III	28–44; 34.5		Plane of cleavage, wall of large chamber
18	II	30–46; 37.9	4237–4700; 4539	Wall of the gallery made by hand tools
19	II	31–50; 39.4	4514–4878; 4706	Wall of the gallery made by hand tools
20	II	30–54; 41.2	4273–4545; 4454	Wall of the gallery driven by blasting operations
21	II	26–52; 41.6	4192–4819; 4568	Wall of the gallery driven by blasting operations
22	II	36–51; 44	4597–4987; 4757	Wall of the gallery made by hand tools
23	II	40–60; 47.5		Plane of cleavage, pillar in large chamber
24	II	40–60; 48.8	5000–5361; 5210	Plane of cleavage, pillar in large chamber

Tab.3 Results of L-type Schmidt hammer rebound hardness R_L measured at investigated parts of rock mass in the Jeroným Mine

Measur. number	Weathering grade	R_L min–max; mean	Description of measured place
1	IV	11–26; 16.1	Wall of the gallery driven by blasting operations
2	IV	14–25; 20	Wall of the chamber made by hand tools
3	IV	13–28; 20.4	Wall of the gallery driven by blasting operations
4	IV	16–30; 21.6	Wall of the chamber made by hand tools
5	IV	18–24; 21.6	Wall of the chamber made by hand tools
6	IV	18.5–28; 23.6	Wall of the chamber made by hand tools
7	IV	18–28; 23.7	Wall of the chamber made by hand tools
8	III	16–31.5; 22.3	Wall of the chamber made by hand tools
9	III	14–32; 22.4	Wall of the chamber made by hand tools
10	III	17–36; 24.4	Wall of the gallery driven by blasting operations
11	II–III	24–45; 33.7	Plane of cleavage, wall of large chamber
12	II–III	33–49; 40.6	Plane of cleavage, wall of large chamber
13	II	30–51; 40.6	Plane of cleavage, pillar in large chamber
14	II	31–61; 44.6	Plane of cleavage, wall of large chamber
15	II	39–57.5; 47	Plane of cleavage, pillar in large chamber
16	II	34–57; 48.1	Plane of cleavage, wall of large chamber

Conclusion

The results of in situ measurements presented in the article proved that the Schmidt hammer rebound testing is effective tool for investigation of the granite rock mass quality and the weathering grade at the locality of the Jeroným Mine, where all of investigations and works have to be realized non-destructively. Rebound hardness was measured in different parts of the mine so that all of weathering grades were investigated–from the slightly weathered rock to the completely weathered rock. Slightly weathered rock has been usually found on the planes of cleavage.

Parts made by hand tools correspond to slightly, moderately and highly weathered rock and parts made by blasting correspond mainly to moderately, highly and completely weathered rock. The results also confirmed necessity of structural pattern consideration in next studies at the locality when evaluating the rock mass quality and weathering. The N-type and L-type of used Schmidt hammers give the similar results, so both hammers can be used at the locality for rock mass quality characterization. Results of multiple impacts measured at one point don´t provide so clear findings in discriminating of the weathering grades. Nevertheless, only four selected planes have been tested for the present and it is necessary to realize measurements at much more planes in the mine to give clearer results using the method of multiple impacts.

Correlation analysis has been carried out to see how the results of the Schmidt hammer rebound testing are comparable with the results of ultrasonic testing measured on the same investigated planes. Obtained Pearson correlation coefficient equal to 0.95 for the UPV and the R_N confirms that both of these non-destructive methods give us the same information about the rock mass quality and the weathering grade.

Information about the rock mass quality and the weathering is important for stability assessment in such a historical mine and for proposing the most suitable stabilizing method to preserve historical parts of the mine in original state. Schmidt hammer rebound testing method is suitable for in situ testing in such a case due to its applicability, easy use and low cost.

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www.geopark.cz

Author

[1]Ing. Markéta Lednická, Ph.D.–The Czech Academy of Sciences, Institute of Geonics, Studentská 1768, 708 00, Ostrava–Poruba, marketa.lednicka@ugn.cas.cz