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USING DIGITAL PHOTOGRAPHS AND ORTHOPHOTOMAPS OF A QUARRY TO ASSESS THE GEOMETRY AND DENSITY OF DISCONTINUITIES IN A SANDSTONE DEPOSIT

WYKORZYSTANIE CYFROWYCH FOTOGRAFII I ORTOFOTOMAPY KAMIENIOŁOMU DO OCENY GEOMETRII I INTENSYWNOŚCI SPĘKAŃ W ZŁOŻU PIASKOWCÓW

A lithological profile and measurements of the orientation and spacings of natural discontinuity planes were carried out in the Górka-Mucharz sandstone excavation (Krosno Beds, Outer Carpathians, Poland). In addition, the density of the discontinuities was assessed by measuring their spacings using oriented digital photographs of the quarry walls. An orthophotomap was also used in assessing the orientation and density of fractures with the tools available in QGIS. It was shown that digital image analysis can be used as an alternative to direct field measurements, especially in situations where access to an outcrop is difficult. The distributions of spacings larger than 40 cm, obtained by direct measurements and based on digital images of the quarry, were comparable. As a consequence, both measurement techniques yielded similar values of the quantity of blocks (QB), which differed by less than 2% for the minimum block volume in the range 0.4-1.0 m^3 and by 6-7% for larger blocks. On the other hand, measurements of discontinuity spacings that were taken on the basis of an orthophotomap can only serve to estimate the approximate maximum value of this parameter. However, the use of orthophotomaps gives a more explicit spatial pattern of the main vertical joint sets than direct measurements in the quarry.

The analysis results also showed the following: (i) the presence of tectonic disturbances visible at the highest level of the deposit; (ii) higher density of set A fractures with planes deepening in the NE direction and a considerable reduction of the QB parameter, particularly in the peripheral NE and SW parts of the deposit; (iii) differences in the orientation of the discontinuity system between particular beds. The variable density of the discontinuities in the excavation is related to the presence of the faults that limit the Górka-Mucharz deposit.

Keywords: dimension stones, Outer Carpathians, Oligocene, Krosno Beds, joint system, quantity of blocks

Przedstawiono profil litologiczny oraz wyniki pomiarów orientacji i odległości naturalnych płaszczyzn podzielności w wyrobisku złoża piaskowców krośnieńskich Górka-Mucharz (Karpaty Zewnętrzne, Polska). Ponadto, intensywność występowania spękań oceniono pomiarami ich rozstępów z wykorzystaniem cyfrowych fotografii zorientowanych ścian kamieniołomu. W ocenie orientacji i intensywności spękań

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wykorzystano też ortofotomapę wykorzystując do analizy narzędzia GIS. Wykazano, że analiza zdjęć cyfrowych może być wykorzystana jako alternatywa bezpośrednich pomiarów terenowych, szczególnie w sytuacji utrudnionego dostępu do odsłonięć. Uzyskane metodą bezpośrednich pomiarów i na podstawie cyfrowych zdjęć kamieniołomu rozkłady rozstępów były zbliżone dla wartości tego parametru powyżej 40 cm. W konsekwencji obie techniki pomiarów dały podobne wartości wskaźnika bloczności (QB), różniące się o niespełna 2% dla objętości bloku minimalnego w zakresie 0,4-1,0 m3 i 6-7% dla bloków większych. Natomiast pomiar rozstępów płaszczyzn podzielności wykonany na podstawie ortofotomapy może służyć jedynie do oceny przybliżonych maksymalnych wartości tego parametru. Jednak, wykorzystanie ortofotomapy daje bardziej jednoznaczny obraz przestrzennej orientacji głównych zespołów pionowych spękań niż pomiary bezpośrednie w kamieniołomie.

W wyniku analizy stwierdzono również: (i) obecność zaburzeń tektonicznych widocznych w najwyższym poziomie złoża; (ii) wyższą intensywność spękań zespołu A o płaszczyznach zapadających w kierunku NE i znaczne zmniejszenie bloczności (QB), szczególnie w peryferyjnych NE i SW fragmentach złoża; (iii) różnice w orientacji systemu nieciągłości odnotowane pomiędzy poszczególnymi warstwami. Ponadto, wykazano, że obecność uskoków ograniczających złoże Górka-Mucharz może wiązać się ze zmienną intensywnością płaszczyzn nieciągłości w wyrobisku.

Słowa kluczowe: oligocen, warstwy krośnieńskie, Karpaty zewnętrzne, system spękań, wskaźnik bloczności, skały bloczne

1. Introduction

One of the main applications of raw rock material is the production of dimension stone. This requires that specific engineering criteria are met, such as physical and mechanical properties and the presence of large blocks of stone, the possibility of whose extraction depends on the system of discontinuities which divides the rock mass. In the case of stratified deposits, e.g. sandstones, the assessment of a reserve of block material starts with identifying the suitable beds of minimum required thickness. Blocks of stone are limited by bedding planes (or by fractures parallel to them) and by more or less vertical fractures (e.g. joints), therefore there is a necessity to perform measurements and analysis of the discontinuity distribution.

The methodology of recording discontinuity data for engineering studies has been described in many articles, e.g. Bieniawski (1984; 1993), Morawski (1973), Piteau (1970), Priest (1993), Priest & Hudson (1976). Nowadays, the orientation and frequency of fractures within rock mass are analysed with very sophisticated software to predict the sizes and shapes of the population of blocks (Abdollahisharif & Bakhtavar, 2009; Kalenchuk et al., 2006; Riquelme et al., 2015; Stavropoulou, 2014; Wang et al., 1991). However, the most essential information required by the owners of dimension stone quarries is the density of fractures and the block yield, which means the amount of extractable and marketable stone blocks (Carvalho et al., 2008; Elçi & Türk, 2014a, 2014b; Mutlutürk, 2007; Sousa et al., 2017a, 2017b). Some authors refer to the ability of rocks to be divided as blockiness (Xia et al., 2016) or block divisibility (Badera et al., 2006; Bromowicz & Figarska-Warchoł, 2012; Thiel 1989). In this work the concept of the quantity of blocks (QB) is used as the proportion (%) of the rock mass of a deposit represented by blocks of more than the required minimum volume (usually 0.4 m^3) that are suitable for further processing. The calculation of this parameter is performed on the basis of discontinuity spacing values as a measure of fracture density.

The purpose of this work is to evaluate the use of orthophotomaps of outcrops and digital photographs of quarry faces for analysis of discontinuity systems and estimation of the quantity of blocks of dimensional stones (QB) as an alternative to direct field measurements. The tectonics described in the literature has also been analysed as a factor of the variability of the QB parameter in sandstone deposits; forecasting these changes during future extraction is of particular importance in the context of rational deposit management and efficient block yield (Bromowicz & Figarska-Warchoł, 2012; Galos et al., 2016; Guzik, 2017).

2. Description of the quarry and geological setting

The Górka-Mucharz deposit was taken as an example. The fine- to medium-grained, muscovite-rich, blue-grey Krosno sandstone that is found in this place is one of the most recognizable rocks in the Polish Outer Carpathians. The fact that it has been quarried for more than 60 years proves its unfailing popularity as a building stone (Bromowicz & Figarska-Warchoł, 2012). Nowadays, it is used as a source of material for the production of dimension stones and crushed aggregates. The WGS84 coordinates of the quarry are 50°31'19'' N, 20°33'28'' E. The area of the deposit is 6.31 ha and its economic resources are 3.277 million tonnes (PGI, 2018).

The first studies of the block production potential of this deposit were performed as part of geological documentation in the 1970s (Znańska, 1974). Since then, new information about the geology of the deposit has been obtained during the extraction process; this is included in the appendix (Nowak, 1988). Research on the relative quantity of minimum-sized blocks of Carpathian sandstones, including the Krosno sandstones of the Górka-Mucharz deposit, was independently conducted by Bromowicz & Karwacki (1975, 1977). The aforementioned investigations were conducted on the basis of standard field measurements. The authors distinguished discontinuity sets by specifying their orientation and calculated the amount of blocks on the basis of spacing distributions. In recent years, an attempt has been made to use shallow seismic refraction techniques to analyse the rock discontinuities in the Górka-Mucharz deposit (Badera et al., 2006). The applied method relatively accurately reflected the main discontinuity directions, but the estimation of fracture linear density was only approximate. An additional (geophysical) index of block divisibility was also proposed.

The Górka-Mucharz deposit is located in the western part of the Silesian Nappe (Polish Carpathians) on the western flank of the Skawa River fault system; more precisely, it is in the most eastern part of the Little Beskid block within the Gilowice-Śleszowice thrust slice, which is composed of prevailing Oligocene Krosno Beds and the underlying Menilite Beds (Cieszkowski et al., 2006; Golonka & Waśkowska-Oliwa, 2007) (Fig. 1). In the deposit there is an exposed fragment of the profile of the Krosno strata; it is slightly dipped to the SSE and is represented by the upper part of the second lithological complex (Moroz-Kopczyńska, 1977). It is composed of thick-bedded sandstones with thin mudstone interlayers.

The edge of the Gilowice-Śleszowice thrust slice, whose general course is along the SW–NE direction, is located several hundred meters from the boundary of the Górka-Mucharz deposit (Fig. 1). This slice is intersected by numerous transverse NW–SE faults, from which the Jaszczurowa fault runs about 400 m west of the boundaries of the deposit, and the Berszcz fault is about 30 m north-east of the quarry border. The latter structure is emphasized in the morphology of the terrain as a steep slope descending in the NE direction. The above discontinuities and the Mucharz and Zagórze faults, which are parallel to them, form a system of step faults that downthrow their eastern walls towards the Skawa valley (Książkiewicz, 1974a, 1974b; Cieszkowski et al., 2006). The relation between the complex fold-fault tectonics of the Silesian Nappe and the joint network recorded in sandstones has already been identified (Mastella & Konon, 2002).

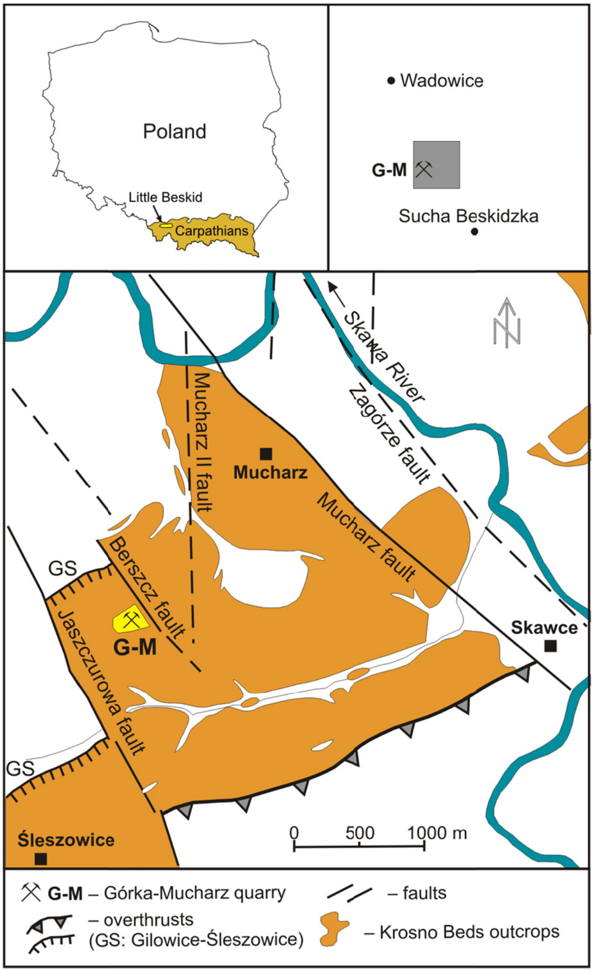

Fig. 1. Location of the Krosno Beds outcrops in the vicinity of Górka-Mucharz quarry (after Książkiewicz, 1974a; Cieszkowski et al., 2006)

3. Methods

3.1. Field measurements of bedding and discontinuities

Based on detailed observations of the exposed part of the sandstone deposit, the basic features of its geological structure were recognized, and a lithological profile was constructed that distinguished the layers of sandstones and shales. Due to the extraction process, the geological works were carried out in 2012-2017.

The orientations of natural discontinuity planes at the lowest levels, V and VI (the location of intensive block stone extraction), were measured by compass recordings of their dip azimuths (δ) and dip angles (α) along horizontal and vertical scanlines at the quarry faces. The values of measured dip azimuths were corrected, because the value of magnetic declination changes over time (ngdc.noaa.gov). Subsequently, the results were projected to the upper hemispherical equal-area net (as is common in Polish works on block-stone assessment), converting the scatter plots into Schmidt contour diagrams that were the basis for identifying the discontinuity system in the quarry. Distances between adjacent discontinuities belonging to the three principal fracture sets (traditionally named A, B and C for longitudinal, transversal, and bedding discontinuity planes, respectively) were directly measured along scanlines and converted into the real values of spacings (a, b and c, respectively) perpendicular to the fracture surfaces. The mean spacings (a_m, b_m and c_m) calculated for different parts of the deposit expressed the measure of fracture density, as was proposed in the methodology developed by Bromowicz & Karwacki (1982a).

3.2. Measurements of discontinuity spacings from digital images of quarry faces

The spacings between discontinuities (i.e. joints, shear, bedding fractures) were determined on the basis of 72 scaled digital photographs of the quarry walls. The tools available in QGIS were used, i.e. image calibration and hand distance measurements. Assignation of the discontinuity to the distinguished sets was conducted on the oriented rock faces. In order to minimize the effect of deformation of spacings due to perspective distortion, each photograph covered a relatively small fragment of the quarry face. The photographs (Fig. 2) had a resolution of 300 dpi, which at the size of the mapped surfaces gave a spatial resolution of 0.1-0.6 cm (mean 0.4 cm). This method made it possible to obtain results in places that were not available for direct measurements; however, due to the resolution limit and the quality of the images (e.g. shadows or overexposed parts of photos) all spacings could not be measured (especially in the lower range).

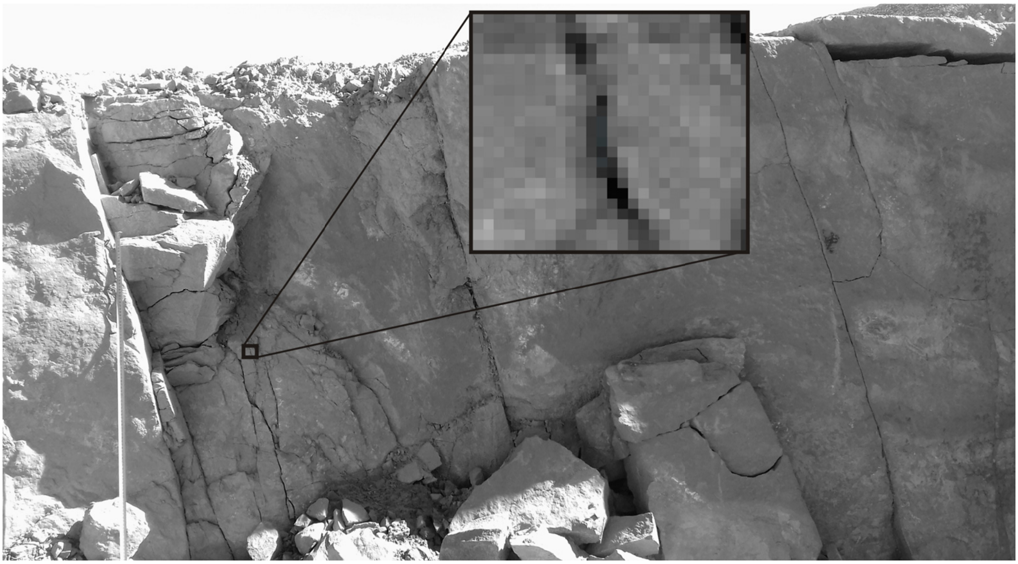

Fig. 2. Traces of subvertical transverse joints of set B (average orientation 302°/86°) in SW wall of the VI level of the Górka-Mucharz quarry. The meter stick visible on the left. The spatial resolution of image – 0.1 cm

3.3. Measurements of discontinuity orientations and spacings from the orthophotomap

The aerial photographs from 2009 that were used to create an orthophoto of the Górka-Mucharz quarry were taken during a period of relatively low excavation intensity, thanks to which traces of joints on the flat top surfaces of the beds were clearly visible. Therefore, an orthophotomap with a spatial resolution of 0.25 m that was provided by the Polish Head Office of Geodesy and Cartography's WMS service on Geoportal 2 (geoportal.gov.pl) and georeferenced in the Polish National Coordinate Reference System (PL_EUREF89/1992) was used to measure the orientation of these discontinuities. It was assumed that the vertical arrangement of these fractures ($\alpha = 90°$) was guided by the results of previous field observations. Thus, the obtained measurements always determined the dip azimuths (δ) of vertical planes. Subsequently, the same orthophotomap was used to measure the spacings between joints that belonged to the distinguished sets. In this case, QGIS tools were also used.

3.4. Calculation of the quantity of blocks (QM)

The evaluation of the quantity of blocks of Krosno sandstones from the Górka-Mucharz deposit was carried out in accordance with the methods developed at the Department of Rock Raw Materials of AGH University of Science and Technology (Bromowicz & Karwacki, 1982a, 1982b). The method requires: (1) the analysis of discontinuity orientations and calculation of dihedral angles (γ) between average planes of the discontinuity sets; (2) the analysis of spacing distribution; (3) the calculation of probabilities of spacings in different value intervals; (4) determination of the most likely shape of blocks by choosing the average parameters of orientation for the three main fracture sets; (5) determination of the dimensions of blocks with the minimum desirable volume; (6) calculation of the quantity of blocks (QB).

The distribution of discontinuity spacings was presented as cumulative histograms with intervals equal to 10 cm for the three principal (the most frequent) discontinuity sets. These histograms were used for calculations of probabilities (respectively p_x, p_y and p_z) of fracture occurrence at distances greater than the appropriate dimensions of the sandstone block (x, y, z) with expected minimum volume (V_{min}). The values of p_x, p_y and p_z correspond to the cumulative percentage of desirable spacings. In turn, the probability of occurrence of minimum-sized blocks was obtained by computing the product of probabilities p_x, p_y and p_z. This made it possible to calculate the quantity of blocks (QB), which is the percentage of blocks larger than the minimum usable volume (usually 0.4 m^3) in the total capacity of the deposit after deducting the interburden and unusable grades. In the case of a non-orthogonal system, the obtained stone blocks have irregular shapes, which causes waste (Fig. 3). Thus, the minimum value of x, y or z must be multiplied by a linear correction coefficient (k). The increased dimensions of the extracted blocks ($k \cdot x$, $k \cdot y$ and/or $k \cdot z$) allow the minimum desirable volume after processing to be obtained (Bromowicz & Karwacki, 1982a). The value of k depends on the geometric relation between the block dimension ratio (e.g. $z/x = c_m / a_m$) and the angle ($\beta = 90° - \gamma$) of deviation from the orthogonality for appropriate discontinuity planes (in the case shown in Fig. 3. this is A and C). This is calculated on the basis of a trigonometric equation (Fig. 3).

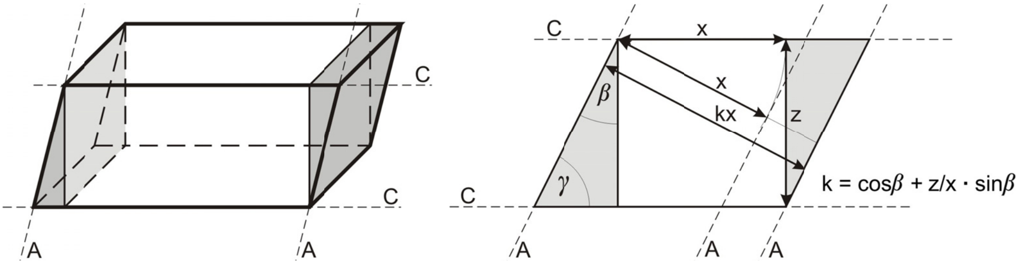

Fig. 3. The shape of stone block in the case of a non-orthogonal disconinuity system and an example of calculation of the correction factor (*k*) used further in QB analysis

4. Results

4.1. Lithological profile

The Górka-Mucharz quarry is a multiple bench excavation on a hillside with seven working levels (Fig. 4). The deposit profile's exposed layers, which are inclined at several degrees (4°-10°) in the NE direction, are mostly thick and very thick sandstone beds interbedded with thin shales (usually up to 20 cm) (Fig. 5). The majority of the sandstones are blue-grey, calcareous, muscovite-rich, and fine-grained with the presence of unevenly distributed flat clay clasts and sporadic coarse-grained sandstone lenticels. They represent a fragment of a sandy Flysch sequence consisting of fluxoturbidities – a greywacke – with good mechanical properties (Figarska-Warchoł & Stańczak, 2016; Peszat C., 1999).

Fig. 4. General view of the Górka-Mucharz quarry and its levels (as at 2017)

In the highest (No. I) bench of the quarry, which has a height of over 20 m, platy and undulated sandstones with visible planar and convolute lamination and various thickness of layers are

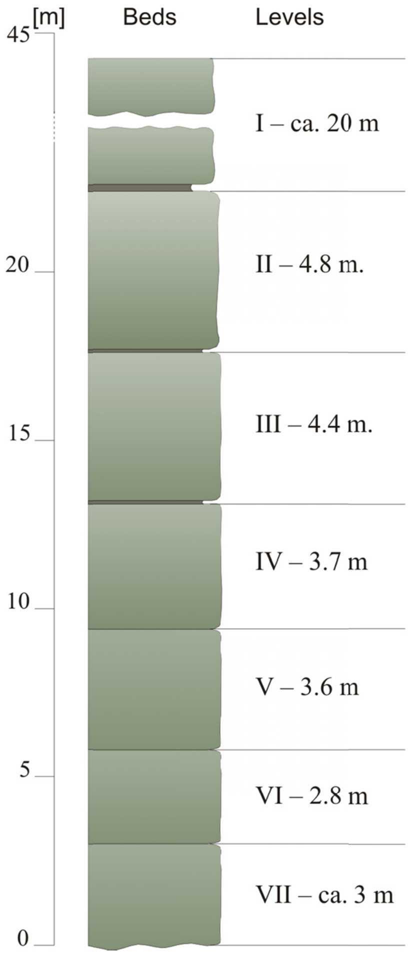

Fig. 5. Lithological profile and levels of the Górka-Mucharz quarry

exposed. They are interbedded by numerous layers of shales. In the faces of this bench there is a NW–SE fault zone which is parallel to the Jaszczurowa fault; it moves down its hanging wall to the east (Fig. 6) and is accompanied by folds and intense fracturing of layers. Sandstones of this level have always been used only for the production of crushed stone aggregates; thus, this part of the profile was not a subject of detailed investigation.

Each of the benches from II to VI are on separate, slightly dipping sandstone beds with thicknesses of 2.8-4.8 m. The share of shales in this part of the profile is approx. 2% (Fig. 5).

Bed II is composed of fine-grained laminated sandstone with the presence of large-scale convolute bedding, which is often associated with the uneven surfaces of the observed discontinuity planes. The lower levels of the quarry (from III to VI) are made of massive blue-grey sandstones with yellowish weathering rinds of a thickness up to 40 cm (15 cm on average) that develop parallel to the joint surfaces. The bottom and top surfaces of beds IV-VI are flat, whereas the tops of beds II and III are clearly undulated with local denivelations of several dozen centimetres.

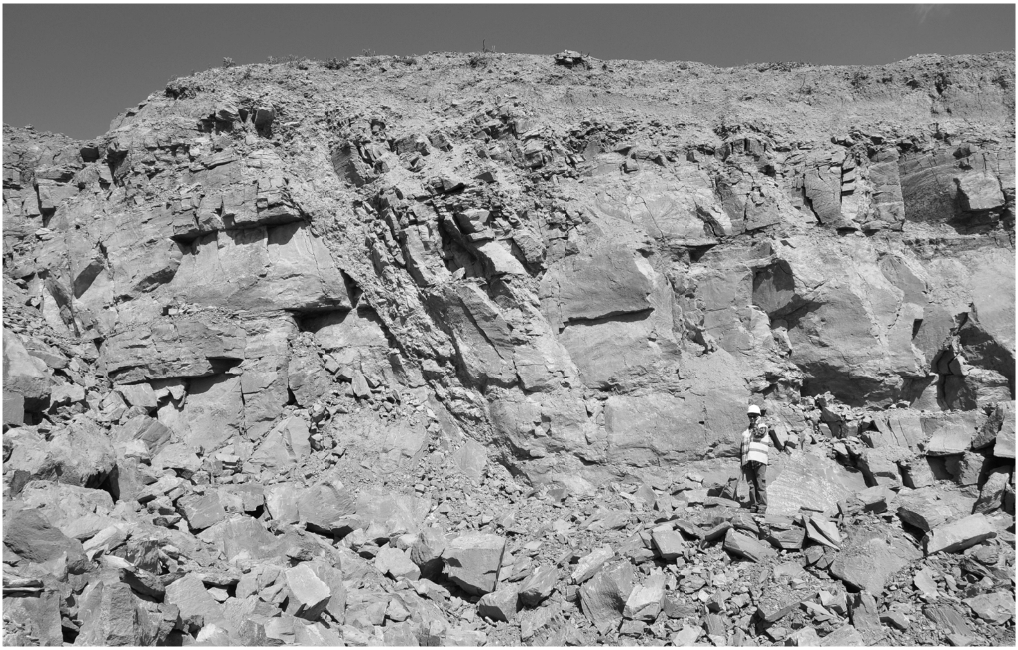

Fig. 6. The NW wall of the uppermost level (no. I) of the Górka-Mucharz quarry with visible fault zone in the centre

In the quarry's lowest partially exposed level (No. VII), which is located in the peripheral NE part of the deposit near the Berszcz fault, a bed of sandstone with a thickness of approx. 3 m is visible. It was not the subject of close observations due to its intense fracturing.

4.2. Discontinuities in the rock mass

4.2.1. Results of field measurements and observations

The natural system of discontinuity planes in the lower part of Górka-Mucharz quarry (levels V and VI) consists of two main sets of subvertical joints (sets A and B) (Fig. 7A) with dips in the range of 76°-90° (Tab. 1). The sub-longitudinal discontinuity planes are developed within a wide range of strikes from 80° to 175°, with two distinguishable subsets: A_1, which has an average strike of ca. 102° (directions in the range from W–E to NWW–SEE); A_2, which has an average strike of ca.138° (NW–SE direction) (Fig. 7B). Due to the detailed analysis of their fracture orientation on the basis of Schmidt point diagrams, these two subsets were distinguished by assuming a limit value of the dip azimuth of 30°. The form and general orientation of their surfaces are similar; therefore, they were included in the common set A during further spacing measurements but the most frequent discontinuities of subset A_1 play the main role in defining the shape of blocks. These subsets are accompanied by transverse joints that are distinctly arranged in the set with an average strike of 33° (set B) (Fig. 7B). The bedding fractures parallel to the bedding planes (the subhorizontal set C) have an average orientation of 45°/9°.

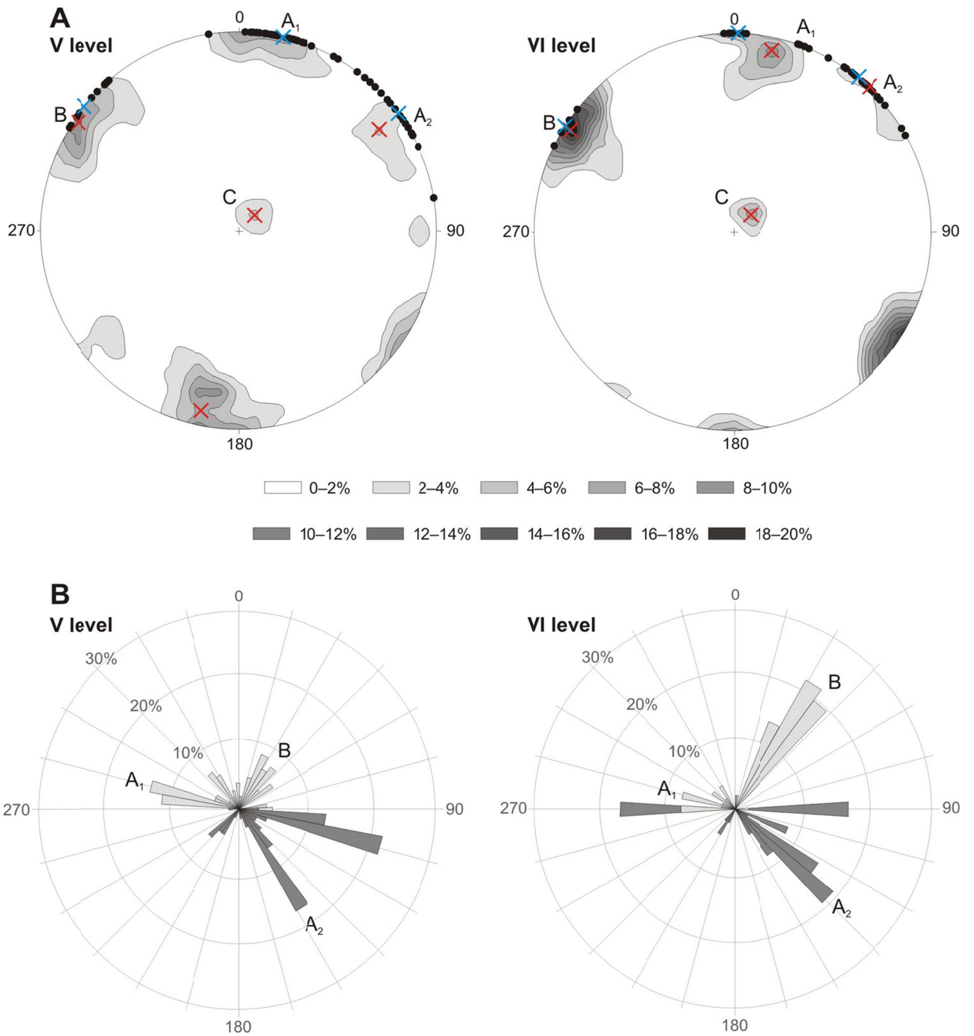

Fig. 7. Orientation of the fractures from the levels V and VI in the Górka-Mucharz deposit.: A – Schmidt contour diagrams, projected on the upper hemispherical equal-area and obtained by direct field measurements (red crosses – the average orientations) with black dots indicating poles of vertical discontinuities visible on the orthophotomap (blue crosses – the average orientations); B – rose-chart of vertical fractures from longitudinal (A1, A2) and transversal (B) sets obtained by direct measurements (light grey) and using orthophoto (dark grey) (the Stereonet software by Richard W. Allmendinger was used)

The subvertical transverse discontinuities (set B) visible in the quarry walls have even surfaces; they are sometimes covered with calcareous crusts and often have almost rectilinear trace development (Fig. 2). The longitudinal planes of discontinuity (set A), which are roughly parallel to the strike direction of the rock strata, are more often characterized than transverse discontinuities by conchoidal and plumose fractures (Fig. 8). The bedding fractures (set C), which often have a slightly uneven surface, usually lose their persistence on vertical discontinuity planes. They

TABLE 1

Average orientation parameters of vertical joint sets in the Górka-Mucharz quarry

Quarry level	H [m]	n	Subset A_1		Subset A_2		Set B		Dihedral angles (γ) between average planes of the joint sets [°]	Deviation from the orthogonality of joint sets $\beta = 90 - \gamma$ [°]
			δ_m [°] δ_{min}–δ_{max}	α_m [°]	δ_m [°] δ_{min}–δ_{max}	α_m [°]	δ_m [°] δ_{min}–δ_{max}	α_m [°]		
			DIRECT FIELD MEASUREMENTS [°]							
V	3.60	114	**192** 170–210	82	**54** 40–80	76	**304** 280–330	88	A_1B: 68 (112); A_2B: 71 (109) A_1C: 90; A_2C: 67 (113) BC: 90	A_1B: 22; A_2B: 19 A_1C: 0; A_2C: 23 BC: 0
VI	2.80	53	**12** 350–360 0–30	83	**43** 30–85	90	**302** 280–320	86	A_1B: 70 (110); A_2B: 79 (101) A_1C: 76 (104); A_2C: 81 (99) BC: 88 (92)	A_1B: 20; A_2B: 11 A_1C: 14; A_2C: 9 BC: 2
			MEASUREMENTS FROM THE ORTHOPHOTOMAP [°]							
II	4.80	28	—	—	—	—	**317** 295–330	90	— — BC: 90	— — BC: 0
III	4.40	10	**25** 20–30	90	**59** 55–65	90	**309** 300–320	90	A_1B: 80 (100); A_2B: 70 (110) A_1C: 81 (99); A_2C: 81 (99) BC: 89 (91)	A_1B: 10; A_2B: 20 A_1C: 9; A_2C: 9 BC: 1
IV	3.70	26	**18** 0–30	90	**58** 50–80	90	**309** 290–320	90	A_1B: 69 (111); A_2B: 71 (109) A_1C: 82 (98); A_2C: 81 (99) BC: 89 (91)	A_1B: 21; A_2B: 19 A_1C: 8; A_2C: 9 BC: 1
V	3.60	68	**13** 350–360 0-30	90	**54** 40–80	90	**309** 295–320	90	A_1B: 64 (116); A_2B: 75 (105) A_1C: 82 (98); A_2C: 81 (99) BC: 89 (91)	A_1B: 26; A_2B: 15 A_1C: 8; A_2C: 9 BC: 1
VI	2.80	47	**6** 355–360 0–30	90	**43** 30–60	90	**302** 295–310	90	A_1B: 64 (116); A_2B: 79 (101) A_1C: 83 (97); A_2C: 81 (99) BC: 88 (92)	A_1B: 26; A_2B: 11 A_1C: 7; A_2C: 9 BC: 2

Explanations: ***H*** – average height of a quarry level, corresponding to a thickness of deposit layer; ***n*** – number of measurements; ***α*** – dip angle and ***δ*** – dip azimuth of joint sets (*m* – mean, min – minimum, max – maximum, determined on the basis of contour diagrams). Dip angle equal to 90° was assumed for all vertical joints visible on the orthophotomap. Orientation parameters of **set C**: 45°/9°.

occur more frequently in the upper parts of the beds, although in many instances there are no additional discontinuities between the bottom and the top of the bed. At higher levels (II and III) the surfaces of the vertical joints are more corrugated than in the lower parts of the deposit.

4.2.2. Results of analysis of the orthophotomap

Using the orthophoto, measurements of strikes for 179 subvertical discontinuities were performed for beds from II, which is at the base of the highest quarry wall, down to bed VI. The results are presented as a discontinuity map with marked limits of the quarry benches (Fig. 9) as well as rose diagrams (Fig. 7B). Due to the assumed 90° dip, the joints are marked on the Schmidt diagrams only in the form of poles (Fig. 7A).

Subsets A_1 and A_2 are more distinctly marked on the orthophotos (Fig. 7A, 7B) than in direct observations and set B is also distinguishable. All the sets are coincident with the sets measured directly in the quarry walls (Fig. 7B). Some observable discontinuities continue in subsequent beds which are not interbedded by shales.

Fig. 8. The NW wall of level V of the Górka-Mucharz quarry with traces of subvertical joints of the set A_1

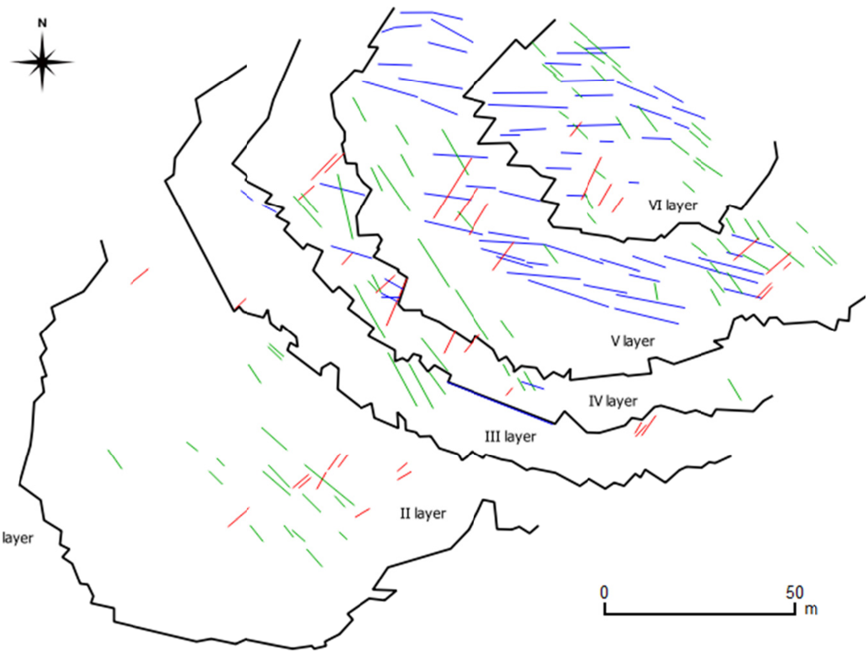

Fig. 9. Map of discontinuity traces grouped into sets: A_1 (blue lines), A_2 (green lines) and B (red lines) visible on the bedding surfaces of the sandstone layers in the Górka-Mucharz quarry (as at 2009). The top surfaces of the succesive layers are numbered on the map

4.3. Analysis of discontinuity spacings

Measurements of spacings a, b, and c, i.e. the perpendicular distances between adjacent discontinuities in sets A, B, and C, respectively, were first performed for level V. In the first stage of these tests, the spacings between the noticeable vertical discontinuity planes of set A (longitudinal subsets A_1 and A_2 taken together) and set B were measured by three methods using: direct field measurements, digital photography of quarry walls and an orthophotomap.

The spacing distributions of vertical joint sets in level V are asymmetric with positive skewness (higher number of small spacing values) (negative exponential) (Fig. 10). Moreover they are bimodal or even multimodal, with a distinct additional local maximum of ca. 75 cm for set A and ca. 95 cm for set B. This is confirmed by measurements performed directly in the quarry and with the use of digital images. The mean values of vertical fracture spacings obtained from the analysis of digital photographs of quarry faces are 21-31 cm higher than those measured

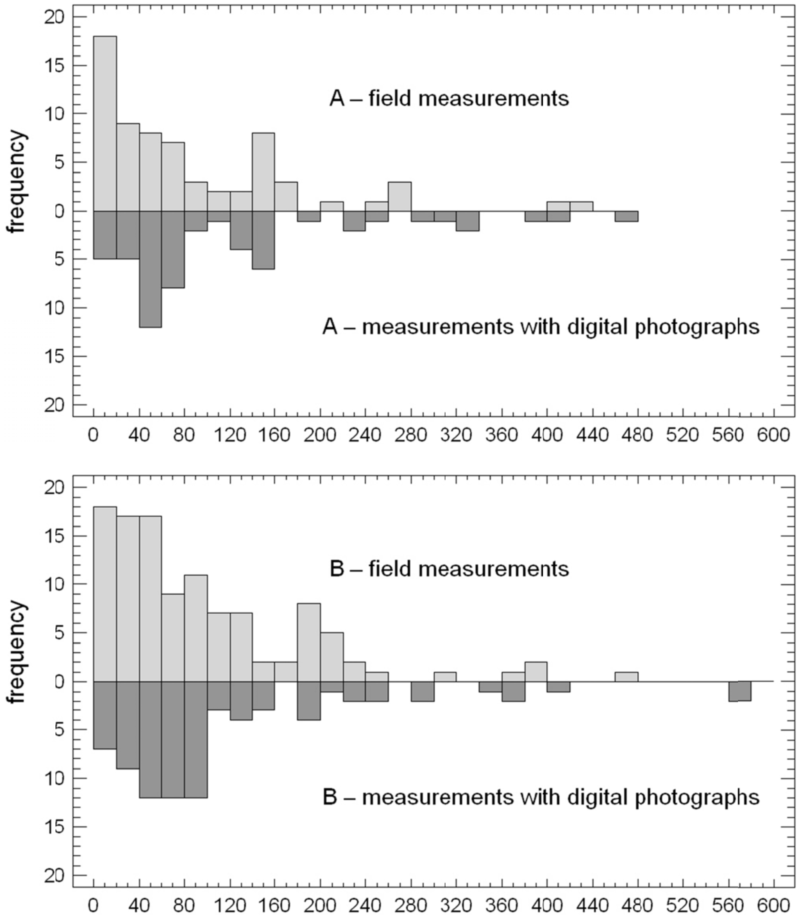

Fig. 10. Distributions of spacings between surfaces of joint sets A and B measured directly in wall faces of the Górka-Mucharz quarry and in their digital photographs (level V of the quarry, as at 2012)

directly (Tab. 2). The spacing distributions in this case are log-normal. The results obtained by the two measurement methods were transformed by the logarithmic function in order to obtain normal distributions of data sets. The comparison of statistics showed that the two samples may come from the same populations because there is not a statistically significant difference between their means (on the basis of a t-test) (except for the means of joint set A, which are similar for measurements above 40 cm), standard deviations (on the basis of an F-test) and distributions (on the basis of a Kolmogorov-Smirnov test) at the 95.0% confidence level (Tab. 3). Comparison of the obtained distributions showed that for vertical discontinuities the frequency of spacings is similar for values above 40 cm (Fig. 10). Fractures of 10-40 cm in the spacing were less frequently visible, and at a distance of a few centimetres they were not found at all in the digital photographs with a spatial resolution of 0.1-0.6 cm.

As a consequence of these results, further measurements of the spacings of discontinuities were taken on the basis of digital photographs of the quarry walls, and direct measurements were taken only on level VI, which was excavated only recently (Tab. 2). From the obtained statistics, it appears that in the entire deposit vertical joints of set B occur in the largest spacings. At levels II-V, the density of the longitudinal joints of set A and the bedding joints of set C increases upwards of the quarry profile, thus changing the shape of the extracted blocks from isometric to flat and elongated.

TABLE 2

Discontinuity spacings for the main discontinuity sets (Górka-Mucharz quarry, as at 2012)

Measurement method:	Set A			Set B			Set C		
	n	a_m $a_{min} - a_{max}$ [cm]	s [cm]	n	b_m $b_{min} - b_{max}$ [cm]	s [cm]	n	c_m $c_{min} - c_{max}$ [cm]	s [cm]
	LEVEL II								
Digital photographs	39	**50** 4–210	47.4	28	**157** 34–428	100.3	52	**67** 2–236	61.0
	LEVEL III								
Digital photographs	30	**97** 14–243	57.2	69	**129** 10–435	100.8	120	**69** 1–333	60.4
	LEVEL IV								
Digital photographs	13	**89** 10–214	79.9	46	**126** 5–599	112.9	42	**88** 10–375	78.4
	LEVEL V								
Field work	67	**90** 6–437	93.9	111	**98** 5–480	90.5	—	—	—
Digital photographs	54	**121** 10–463	111.7	79	**119** 13–580	117.6	91	**137** 16–410	115.0
Orthophotomap	33	**188** 68–361	85.0	32	**142** 65–465	84.1	—	—	—
	LEVEL VI								
Field work	97	**54** 2–320	56.3	62	**76** 4–291	75.5	51	**61** 3–250	54.8
Orthophotomap	39	**192** 77–422	92.7	22	**142** 91–274	51.2	—	—	—

Explanations: ***n*** – number of measurements; ***a***, ***b*** and ***c*** – spacings of joints in the set A, B and C, respectively (*m* – mean, min – minimum, max – maximum); ***s*** – standard deviation of spacings.

TABLE 3

Comparison of distributions of vertical discontinuity spacings obtained from direct measurements and using digital photographs of Górka-Mucharz quarry walls

Statistic test	Discontinuity set A	Discontinuity set B
F-test to compare Standard Deviations (*sd*) Null hypothesis: $sd1 = sd2$	$F = 1.417$ P-value = 0.191	$F = 1.246$ P-value = 0.304
Student's t-test to compare means (*m*) Null hypothesis: $m1 = m2$	$t = -2.270$ P-value = 0.025	$t = -1.627$ P-value = 0.105
Kolmogorov-Smirnov test to compare the distributions of the two samples DN – the maximum vertical distance between the cumulative distribution function of the two samples	DN = 0.248 P-value = 0.051	DN = 0.1503 P-value = 0.249

Theoretically, the spatial resolution of the orthophotomap could make it possible to distinguish lineaments (the traces of fracture sets A and B) when they are at least 25 cm apart. However, in practice this method made it possible to measure spacings with a minimum value of 65 cm. The mean values for particular levels are double the mean spacings obtained in direct field measurements, and in the case of discontinuities of set A at level VI they are up to 4 times more (Tab. 2). The spacing distributions from the orthophotomap are similar to those from digital photographs and direct measurements only within a range over 200 cm.

4.4. Analysis of the quantity of blocks

The planes of discontinuity in the deposit influence the shape of the rock blocks extracted from it. From the point of view of block production, cuboidal forms that comply with the orthogonality condition (i.e. deviations of the angle β between two adjacent walls from a right angle is less than 15°) are most advantageous. In order to assess the most probable shape of blocks, three principal discontinuity sets (A_1, B and C) were chosen due to their frequency of occurrence. The discontinuities of subset A_2 were relatively rare in the field observations. Moreover, the choice of set A_1 provided the opportunity to take into account a stronger deviation (β) from the orthogonality between the selected vertical sets (A_1 and B) than in the case of sets A_2 and B (Tab. 1). The small number of directly observed discontinuity planes of set C and the lack of a way to determine its orthophotomap parameters resulted in the same 45°/9° orientation being assumed for it in all levels. The obtained results showed that in all cases, except for level III, the orthogonality condition was not met mutually by the planes of sets A_1 and B (Tab. 1).

The spacing distributions and mutual orientation of the sets were used to determine the dimensions (x, y, z) of blocks, whose percentage in the deposit volume was then calculated as the quantity of block product (QB). The ratio of the $x : y : z$ dimensions matched the relations of the mean spacings in the relevant joint sets $a_m : b_m : c_m$; however, due to the lack of orthogonality between the planes of sets A_1 and B, the dimensions obtained in this way had to be adjusted accordingly by the value of the correction factor (k). Depending on the ratio of $b_m : a_m$ and angular deviation β for sets A_1 and B, this correction ranged from 1.21 to 2.12, thus increasing the minimum expected dimension, x. In addition, the presence of yellowish weathering rind with an average width of 15 cm that accompanied the natural joints required each dimension of the block to be increased by an additional 30 cm. This part of blocks is usually waste during processing.

4.4.1. QB for selected bed

The cumulative percentages of fracture spacings (Tab. 4), which constitute the probability of occurrence of discontinuity at distances larger than the expected dimensions of minimum sandstone block (*kx*, *y*, *z*), were used to calculate the quantity of blocks. For selected level (bed) V, this analysis was performed on the basis of joint spacings measured by the three methods described in the Method chapter; their orientations were derived from direct observations and the orthophotomap. The quantity of blocks gained from spacings obtained from direct measurements and from analysis of digital images is very similar, especially for smaller blocks (Tab. 5). In turn, spacing measurements based on an orthophotomap caused a significant overstatement of the quantity of blocks of volume up to 1 m^3 by as much as 20%. In the case of larger blocks with linear dimensions in the range 130-200 cm, the calculated QB parameter is similar to that obtained by other methods.

Regardless of the method used to measure the spacings between joints, the results of analysis of the block size distribution in level V indicate a predominant percentage of very large blocks of volume greater than 2.0 m^3 (Fig. 11). These are accompanied by a large quantity of small blocks (0.5-1.0 m^3), while the share of very small blocks (0.4-0.5 m^3) and large blocks (1.0-2.0 m^3) was insignificant. The described relations are affected by the occurrence of large spacings between

TABLE 4

Probabilities of spacings at distances greater than the lower limits of successive intervals, obtained by different methods of measurement (level V of the Górka-Mucharz quarry, as at 2012)

Spacing intervals [cm]	Discontinuity set A			Discontinuity set B		
	Field work	Digital photographs	Orthophoto	Field work	Digital photographs	Orthophoto
0–9	1.000	1.000	1.000	1.000	1.000	1.000
10–19	0.990	0.998	1.000	0.994	0.998	1.000
20–29	0.969	0.989	1.000	0.977	0.989	1.000
30–39	0.946	0.977	1.000	0.955	0.976	1.000
40–49	0.924	0.964	1.000	0.932	0.959	1.000
50–59	0.898	0.931	1.000	0.902	0.932	1.000
60–69	0.864	0.885	0.997	0.867	0.892	0.996
70–79	0.823	0.845	0.989	0.836	0.852	0.981
80–89	0.785	0.803	0.976	0.810	0.813	0.951
90–99	0.762	0.770	0.966	0.777	0.761	0.893
100–109	0.743	0.760	0.950	0.730	0.707	0.791
110–119	0.713	0.756	0.911	0.677	0.672	0.690
120–129	0.686	0.743	0.861	0.628	0.655	0.608
130–139	0.666	0.714	0.810	0.586	0.635	0.540
140–149	0.644	0.662	0.768	0.553	0.602	0.505
150–159	0.607	0.595	0.745	0.538	0.572	0.480
160–169	0.530	0.543	0.713	0.527	0.556	0.438
170–179	0.429	0.526	0.667	0.512	0.551	0.393
180–189	0.367	0.518	0.648	0.488	0.541	0.365
190–199	0.352	0.504	0.640	0.450	0.511	0.334
>200	0.264	0.372	0.470	0.317	0.363	0.230

TABLE 5

Comparison of quantity of blocks (QB) in the level V of the Górka-Mucharz quarry calculated for spacing values obtained by various types of mesurements and for various minimum block sizes

Minimum block size [m³]	Quantity of blocks (QB) for the spacings resulted by various methods of measurements:		
	Field work(1)	Digital photographs (1)	Orthophotomap(2)
0.4	39.6%	41.5%	62.4%
0.5	38.3%	39.9%	57.1%
1.0	27.1%	28.7%	36.3%
1.5	15.6%	22.7%	26.8%
2.0	12.6%	18.9%	22.7%

Explanations: The orientation of joint sets was taken from: (1) direct field measurements, (2) orthophotomap.

joint surfaces (over 200 cm). This is confirmed by the quarry operator, according to whom blocks with dimensions of 1.8 m × 3.0 m × 1.5 m are frequently extracted (oral information).

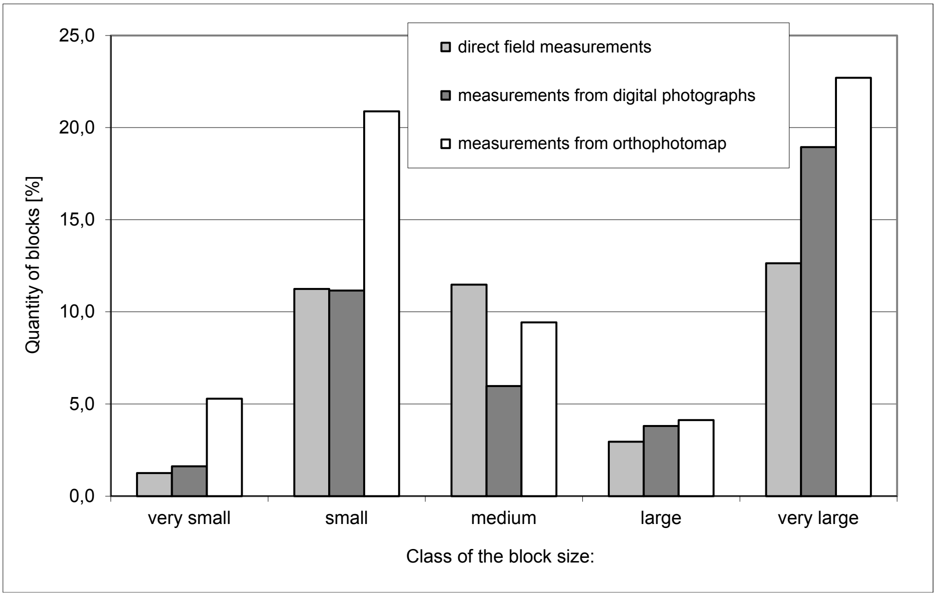

Fig. 11. Quantity of blocks of various sizes at the level V of the Górka-Mucharz quarry calculated on the basis of measurements from direct field work, digital photographs of wall faces and analysis of orthophotomap

4.4.2. QB for individual beds

For other deposit beds the analysis of spacing distribution was performed on the basis of spacing measurements conducted with the use of digital images of quarry walls (except for level VI, where direct measurements were used). The choice of this measurement method was a consequence of the obtained results, as is described below. (1) The examination of spacings in level V showed that the percentage of spacings in the range 0-40 cm in relation to the length of the entire scanline was only ca. 8% for set A and ca. 7% for set B in direct measurements, while for measurements from digital photographs it was ca. 3% and 4%, respectively. Thus, the low amount of the smallest spacings is not significant for the probability of the occurrence of discontinuity planes at distances of 50-170 cm, which correspond to the linear dimensions of the minimum block. In the above range of spacings the probability differs by less than 0.06 (usually up to 0.04) between direct measurements and with the use of photos (Tab. 4; Fig. 12). (2) Assuming quite an unfavourable overestimation for the analysis of digital photographs, the discussed probability values for all three major discontinuity sets is 0.04; the maximum difference between the obtained value of the quantity of blocks (QB) in comparison to the result for direct measurements will be 11.53% (see example in Tab. 6).

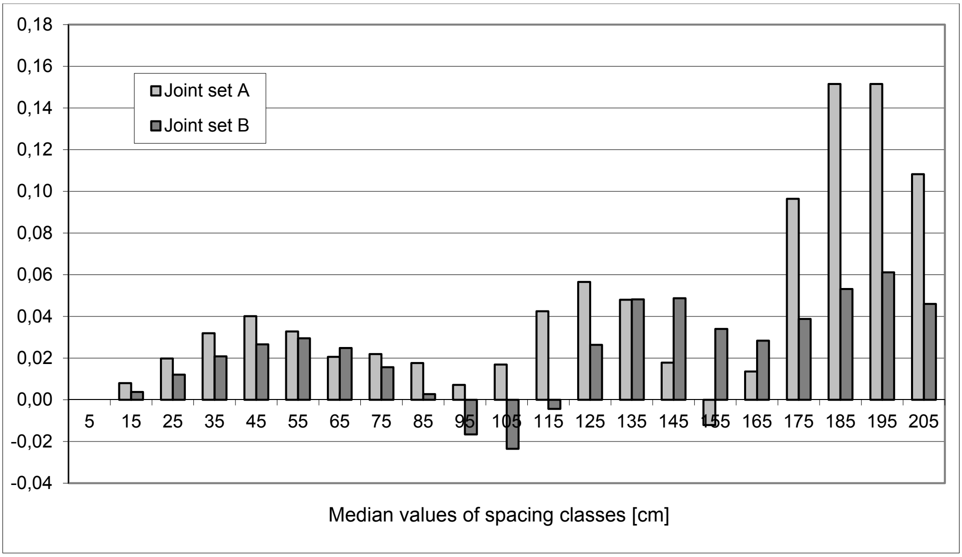

Fig. 12. Differences in probabilities of spacings at distances greater than the lower limits of successive classes, obtained by subtracting probabilities for two methods of measuring: by direct field measurements and with use of digital photographs (V level of the quarry, as at 2012)

According to the information presented above (chapter 4.2.2.), in the measurement of the orientation of discontinuity planes it is appropriate to use aerial photographs that are converted to an orthophotomap. Such data, together with spacings from digital photographs, were used in the calculations of the quantity of blocks for individual beds of the Górka-Mucharz deposit (Tab. 7).

Regardless of the assumed size of the minimum block, an increase in the quantity of blocks (QB) down the deposit profile from level II to level V is noticeable; this parameter falls again in level VI, which is the lowest currently excavated. Similar information was obtained from the quarry operator, according to whom levels IV and V were once characterized by the highest amount of marketable dimension stones, which used to represent as much as 50% of the block yield (nowadays QB is slightly lower), while in level VI it is only a few percent. In turn, due to the irregular shape, size, and share of blocks, levels II and III are intended for the production of crushed-stone aggregate. It was also found that the percentage of very large blocks decreases,

TABLE 6

An example of calculation of the quantity of blocks (QB) in the case of hypothetical disadvantageous high difference between results obtained by two different methods of spacing measurements

Type of measurement	**Dimensions of block of minimum volume**	**Maximum theoretical probability of discontinuity occurrence at distances greater than appropriate block dimensions (the assumed difference between probabilities equal to 0.04)**	**Quantity of blocks QB = $p_x \times p_y \times p_z \times 100\%$**
Field work	x y z	$p_x = 0.96$ $p_y = 0.96$ $p_z = 0.96$	$QB_1 = 0.96 \times 0.96 \times 0.96 \times 100\%$ $QB_1 = 88.47\%$
Digital photographs	x y z	$p_x = 0.96 + 0.04 = 1.00$ $p_y = 0.96 + 0.04 = 1.00$ $p_z = 0.96 + 0.04 = 1.00$	$QB_2 = 1.00 \times 1.00 \times 1.00 \times 100\%$ $QB_2 = 100\%$
Value of overestimation of QB:			$QB_2 - QB_1 = 11.53\%$

TABLE 7

Quantity of blocks (QB) in levels II–VI of the Górka-Mucharz quarry calculated for various minimum block sizes

Minimum block size [m^3]	**Level II$^{(1)}$**	**Level III$^{(1)}$**	**Level IV$^{(1)}$**	**Level V$^{(1)}$**	**Level VI$^{(2)}$**	**Weighted mean of QB for levels II–VI**
0.4	11.1%	23.4%	42.9%	41.9%	9.7%	**25.5%**
0.5	8.0%	21.4%	35.4%	41.5%	7.0%	**22.4%**
1.0	3.1%	7.2%	27.8%	28.7%	3.3%	**13.6%**
1.5	1.8%	1.9%	14.2%	22.7%	1.8%	**8.1%**
2.0	1.7%	1.0%	7.6%	19.5%	1.5%	**6.0%**
Thickness of deposit layers (weights)	4.80 m	4.40 m	3.70 m	3.60 m	2.80 m	S = 19.3 m

Explanations: Calculations made on the basis of: (1) spacings from digital photographs and joint orientation from orthophotomap, (2) direct field measurements of spacings and joint orientation. Thickness of deposit layers used as weights.

and the raw block material generally becomes finer up the deposit profile. In level V, small and very small blocks (0.4-1.0 m^3) have a share of 31.6%, while in level II they constitute almost ¾ (72.5%) of the volume of the dimension stone material.

The QB parameters obtained by measuring joint spacings from quarry digital photographs and their orientation from the orthophotomap also correspond with the results obtained by the geologists who previously explored and assessed the deposit's parameters (Znańska, 1974; Nowak, 1988). The QB value for the whole thick-bedded complex of the deposit profile, with an assumed anisotropic shape of blocks of minimum size of 0.5 m^3 (calculated on the basis of measurements from the exposures and boreholes) was then 22.4%, and for blocks over 1.0 m^3 it was 14.5%. Similar values were obtained as a result of the calculations described in this article: 22.4% and 13.6%, respectively.

5. Discussion

The analysis of fracture orientation revealed that the system of discontinuities in the Górka-Mucharz sandstone deposit consists of three principal sets: two subvertical and one parallel to the bedding. The bearings of the subvertical joints coincide with the directions of tectonic structures such as the Berszcz and Jaszczurowa faults, as well as with the edge of the Gilowice-Śleszowice thrust slice, which surrounds the area of the deposit (Fig. 1). Intensive fracturing is observed in the most north-eastern and south-western parts of the quarry near the aforementioned faults.

The results of discontinuity analysis based on the orthophoto of the lower levels (V and VI) of the quarry show that some sets of lineaments are distinguishable (Fig. 9) whose strike directions are similar to those obtained by direct measurements (means of dip azimuths are the same or differ by several degrees) (Tab. 1, Fig 7). Therefore, the orthophotomap can be used in the assessment of fracture orientation provided that the dips of discontinuity planes have been identified previously (e.g. by field reconnaissance or on the basis of the literature).

Moreover, the presence of discontinuities which are a result of the extraction method, e.g. blasting, might cause difficulties or even make it impossible to use traditional field measurements with a compass. These discontinuities are developed in a relatively shallow zone from the exposed face walls. Thus, the analysis of fractures visible on the top surfaces of beds (e.g. on the orthophoto) away from the quarry walls could be a solution as a complementary method of measurements.

Another research problem when using a compass is related to the uneven, corrugated surface of some fractures. Depending on the location of the measurement, the orientation of such planes varies greatly. This results in the complex joint system pattern that is visible on the diagram in the case of a limited number of possible measurements. However, lineaments that represent discontinuities on the aerial photograph yield their averaged orientations.

The discontinuity map (Fig. 9) and the results of the orientation measurements for each quarry level (Tab. 1) indicate the presence of zones with a dominance of different joint sets within the whole deposit, or even within a single bed. For example, in the northern part of level VI, joint sets A_1 and A_2 play the main role, while in the south direction set B gains importance and determines, together with the planes of set A_1, the shapes of the blocks in these places. Moreover, for individual joint sets a gradual change of discontinuity orientations is sometimes noted at a distance of several dozen meters. An example might be the joints of set A_1, which in the northern part of levels V and VI have dip azimuths near 0°, and in the SE direction their values increase, practically corresponding here with set A_2 (a 30° limit value of dip azimuth was assumed on the basis of analysis of discontinuity distribution). It follows that in order to properly assess the system of joints, the measurements of their orientation should be repeated periodically as the extraction progresses through the rock mass, both in direct field studies and with the use of an orthophotomap.

An interesting relation was revealed when analysing the dip azimuths of discontinuity planes in subsequent beds. Their values for all subvertical joint sets increased from level VI to level II. Thus, the joints of set A_1, whose planes at level VI dip in a mean direction of 6°, reach mean dip azimuths up to 25° at level III, while set A_2 changes its average orientation from 43° to 59° azimuth, and set B changes from 302° to 317° up to level II (Tab. 1). More evidence for the fluctuating orientation of the joint system up the lithological profile is provided by the result obtained by Bromowicz & Karwacki in 1975. They found joints with prevailing dip azimuths of 10°-20°, 60°-80° and ca. 340° on the basis of 437 measurements in the upper part of the deposit profile exposed at that time, i.e. the blocky, lower part of level I and levels II-IV. Such a joint system is similar to the one observed nowadays in levels IV-V. It should be also emphasized that the faces of the working walls of the aforementioned levels were then located more towards the NE direction, where levels IV-V are currently being extracted. Thus, it can be stated that the orientation of the joint sets observed in the subsequent levels of the deposit, situated from SW to NE, has changed in total by over a dozen degrees.

The orientation of the joint system might vary in the vertical direction together with the considered part of the deposit profile, as joints sometimes continue in subsequent levels (beds); alternatively, the orientation might vary horizontally and depend on the current location of the examined exposure. The observed differences in joint orientation between the excavation benches might be due to the fact that subsequent parts of the deposit are being exposed along the NE–SW line as the extraction process proceeds. It is possible that the stress fields that affect various parts of the rock mass of the deposit were different. The orientations of vertical discontinuities correspond to the directions of nearby faults and thrust lines, which may indicate their relation, but the purpose of this paper is not to understand the origin of the fractures.

The spacing distributions obtained with the use of digital photographs and direct measurements are similar, especially for values above 40 cm. Further analysis of the hypothetical disadvantageous case of overestimating the probability of appropriate spacings showed that differences in the quantity of blocks (QB) will be less than 12%. These results allow us to assume that digital images of quarry walls can be used for spacing measurements in combination with or even instead of direct field work. This is particularly important in situations in which direct access to quarry walls is difficult. On the other hand, the attempted use of an orthophotomap in the process of spacing measurements did not produce favourable results, therefore it can only be used to predict approximate maximum values of this parameter. The analysis of the QB parameter in the lower part of the quarry (level V) revealed that it is also possible to estimate the share of large and very large blocks in the deposit if a relatively good quality orthophotomap with visible traces of discontinuities is available.

The general view of the variability of the quantity of blocks parameter in the Górka-Mucharz sandstone deposit might be affected by the presence of fault zones that limit it from NE and SW; therefore distinct tectonic phenomena, i.e. folds or faults, are observed at working levels I, VI, and VII. An additional factor that influences the amount of sandstone blocks is the proximity of the terrain surface on the hillside to the actually exploited parts of the deposit. This is especially evident in the newly opened benches VI and VII, where relaxation processes followed by weathering are conducive to the formation of a more intense network of fractures. On the other hand, as signalled by the owner of the deposit, the reduction of the share of blocks in levels IV-V in recent years can be attributed to the moving of the face of the excavation in the SW direction (in 2010-2016 by approx. 25 m), where the impact of fault tectonics should be expected to increase. Therefore, further reduction of the quantity of blocks is expected at levels II-V as the extraction process continues in the current direction. In contrast, the value of QB will probably increase at levels VI-VII.

6. Conclusions

The blue-grey, medium, and fine-grained muscovite sandstones from the Górka-Mucharz deposit are exploited for the production of dimension stones and crushed aggregates. The main source of suitable blocks in this quarry are levels IV and V, where massive sandstones are exposed that form beds with an average thickness of 3.70 m and 3.60 m, respectively. The natural planes of discontinuity observed within them create a complex system consisting of three vertical joint sets with dip azimuths in the ranges 170°-210° for A_1, 40°-80° for A_2, and 280°-330° for B. They are accompanied by a set of bedding joints with an average orientation of 45°/9°.

The analysis of the joint system showed that the orientations of joints vary by a dozen or so degrees between levels II-VI, progressing along the direction of mining works in the SW–NE line. Sometimes the orientation of individual joint sets measured within one level differs in the proximity of several dozen meters. A vertical continuation of joints was also observed in the subsequent sandstone beds. Therefore, in order to correctly predict the development of the discontinuities in the rock mass, it is proposed to periodically repeat the measurements of their orientation as the extraction process continues.

The measurements of the orientation of lineaments (traces of joints on the top surfaces of the sandstone beds) that are visible on the orthophotomap revealed that such a method can provide information about the main sets of joints with an accuracy similar to direct measurements in the exposures. Additionally, the picture of the spatial orientation of the joint system obtained from the processed aerial photographs is more explicit because the best-developed discontinuities were analysed and the strike azimuth of joints with uneven surfaces represents averaged values measured directly in the quarry wall. The condition for the proper use of this data is the previous identification of joint dips. Unfortunately, measurements of joint spacings using the same orthophotomap fragments can only serve to predict the approximate maximum values of this parameter.

Measurements of joint spacings using the appropriate quality digital photographs of the oriented quarry faces can be used as an alternative to direct measurements, especially when access to the wall is difficult. In that case, to which set of fractures the visible traces belong must be determined in advance. Application of this method allowed mean values to be obtained that deviated from the results of direct field investigations by 20-30 cm, with a similar distribution for spacings above 40 cm. Consequently, for each class of spacings both methods provided similar values of probability of their occurrence, and as a result the obtained quantity of blocks (QB) differed by less than 2% for the minimum block size in the range of 0.4-1.0 m^3 and 6-7% for the larger blocks.

Because of the lack of right angles between the joints of some sets and the presence of weathering rinds that had developed in the sandstones at an average depth of 15 cm along the natural discontinuity planes, the dimensions of blocks extracted from the quarry should be increased in order to obtain marketable stone blocks of minimum expected volume. The consequence of this is the reduction of the calculated geological quantity of blocks (QB), which for a block with a minimum volume of 0.5 m^3 reaches the highest values of 35%-42% in levels IV and V. This quantity decreases to several percent at the highest and lowest levels of the quarry. In practice, block yield might be lower due to the use of explosives, the share of shales in the bed profile, and the presence of accumulations of shale clasts and coarse-grained sandstone lenticels.

It can be concluded that the tectonic structures surrounding the area of the deposit from the SW and NE (i.e. Jaszczurowa and Berszcz fault zones) influence the system of discontinuities observed in the quarry walls. This might be evidenced by: (i) the presence of faults at the highest level of the quarry (level I); (ii) greater density of discontinuities of set A with planes dipping in the NE direction compared to fractures of set B; (iii) a significant reduction in the quantity of blocks in the peripheral parts of the deposit, which are exposed at levels I-II and VI-VII. As a result, the approach of the mining front of all deposit levels to the tectonically involved SW and NE fragments of the deposit will lead to decreased block yield. On the other hand, the central part of the deposit area (levels IV, V, and possibly also VI in the future) may still be a source of attractive dimension stones.

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References

Abdollahisharif J., Bakhtavar E., 2009. *An intelligent algorithm of minimum cutting plane to find the optimal size of extractable-blocks in dimension stone quarries*. Archives of Mining Sciences **54**, 4, 641-656.

Badera J., Niemczuk S., Tomaszewska R., 2006. *Application of the shallow refraction seismic method for analysis of block divisibility of Carpathian sandstones in the Górka-Mucharz deposit*. Publs. Inst. Geophys. Pol. Acad. Sc. M-29 (395).

Bieniawski Z.T., 1984. *Rock Mechanics Design in Mining and Tunneling*. A.A. Balkema, Rotterdam, Boston, 272.

Bieniawski Z.T., 1993. *Classification of Rock Masses for Engineering: The RMR System and Future Trends*. [in:] Hudson J. A. (ed.) Comprehensive Rock Engineering. Principles, Practice & Projects. Pergamon Press, Oxford, New York, Seoul, Tokyo, 553-573.

Bromowicz J., Figarska-Warchoł B., 2012. *Kamienie dekoracyjne i architektoniczne południowo-wschodniej Polski – złoża, zasoby i perspektywy eksploatacji*. Gospodarka Surowcami Mineralnymi – Mineral Resources Management 28, 3, 5-22.

Bromowicz J., Karwacki A., 1975. *Bloczność materiałów kamiennych na tle ich geologii i własności technicznych. Bloczność złóż piaskowców budowlanych Gór Świętokrzyskich i Karpat*. Centralny Ośrodek Badawczo-Rozwojowy Przemysłu Kamienia Budowlanego „PROKAM" w Krakowie, Archiwum Pracowni Złóż Surowców Skalnych, WGGiOŚ AGH.

Bromowicz J., Karwacki A., 1977. *Możliwości uzyskiwania bloków z polskich złóż piaskowców budowlanych*. Górnictwo Odkrywkowe 9-10, 280-284.

Bromowicz J., Karwacki A., 1982a. *Metodyka badań bloczności złóż budowlanych materiałów kamiennych*. Geologia 8, 2, 51-76.

Bromowicz J., Karwacki A., 1982b. *Geologiczne podstawy klasyfikacji bloczności złóż kamieni budowlanych*. Przegląd Geologiczny 4, 173-175.

Carvalho J.F., Heriques P., Falé P., Luís G., 2008. *Decision criteria for the exploration of ornamental-stone deposits: Application to the marbles of the Portuguese Estremoz Anticline*. International Journal of Rock Mechanics & Mining Sciences **45**, 1306-1319.

Cieszkowski M., Golonka J., Waśkowska-Oliwa A., Chrustek M., 2006. *Budowa geologiczna rejonu Sucha Beskidzka – Świnna Poręba (Polskie Karpaty fliszowe)*. Geologia **32**, 2, 155-201.

Elçi H., Türk N., 2014a. *Rock mass block quality designation for marble production*. International Journal of Rock Mechanics & Mining Sciences **69**, 26-30.

Elçi H., Türk N., 2014b. *Block Volume Estimation from the Discontinuity Spacing Measurements of Mesozoic Limestone Quarries, Karaburun Peninsula, Turkey*. Scientific World Journal, 2014, 1-10.

Figarska-Warchoł B., Stańczak G., 2016. *Wpływ petrograficznego zróżnicowania piaskowców krośnieńskich na ich właściwości fizyczno-mechaniczne w złożach Górka-Mucharz i Skawce (Beskid Mały)*. Zeszyty Naukowe IGSMiE PAN **96**, 37-56.

Galos K., Guzik K., Stachowiak A., 2016. *Wstępna ocena opłacalności podziemnej eksploatacji kamieni blocznych w Polsce*. Mining Science – Mineral Aggregates **23**, 23-36.

Golonka J., Waśkowska-Oliwa A., 2007. *Stratygrafia polskich Karpat fliszowych pomiędzy Bielskiem-Białą a Nowym Targiem*. Geologia **33**, 4/1, 5-28.

Guzik K., 2017. *Możliwości wykorzystania piaskowców jurajskich północno-zachodniego obrzeżenia Gór Świętokrzyskich jako kamieni architektonicznych w zależności od ich litologii*. Wydawnictwo IGSMiE PAN, Kraków.

Kalenchuk K.S., Diederichs M.S., McKinnon S., 2006. *Characterizing block geometry in jointed rockmasses*. International Journal of Rock Mechanics & Mining Sciences **43**, 1212-1225.

Książkiewicz M., 1974a. *Szczegółowa Mapa Geologiczna Polski w skali 1:50000, ark. Sucha Beskidzka*. Wydawnictwa Geologiczne, Warszawa.

Książkiewicz M., 1974b. *Objaśnienia do Szczegółowej Mapy Geologicznej Polski w skali 1:50000, ark. Sucha Beskidzka*. Wydawnictwa Geologiczne, Warszawa.

Mastella L., Konon A., 2002. *Jointing in the Silesian Nappe (Outer Carpathians, Poland) – paleostress reconstruction*. Geologica Carpathica **53**, 5, 315-325.

Morawski W., 1973. *Gęstość ciosu w piaskowcach fliszowych wschodniego Podhala*. Biuletyn Geologiczny UW 15, 233-255.

Moroz-Kopczyńska M., 1977. *Litologia piaskowców krośnieńskich w obszarze między Istebną i Myślenicami w świetle ich wykorzystania w przemyśle materiałów budowlanych*. Prace Geologiczne PAN 104, 66.

Mutlutürk M., 2007. *Determining the amount of marketable blocks of dimensional stone before actual extraction*. Journal of Mining Science 43, 1, 67-72.

Nowak T.W., 1988. *Dodatek nr 2 do dokumentacji geologicznej złoża piaskowców krośnieńskich „Górka-Mucharz" w kat. B+C1*. Przedsiębiorstwo Geologiczne, Kraków.

Peszat C., 1999. *Właściwości strukturalno-teksturalne i geneza spoiw węglanowych gruboławicowych piaskowców jednostki śląskiej (Polskie Karpaty fliszowe)*. Gospodarka Surowcami Mineralnymi 15, 1, 65-104.

PGI, 2018. The Polish Geological Institute – National Research Institute. *System Gospodarki i Ochrony Bogactw Mineralnych MIDAS*. [Online] Dostępne w: geoportal.pgi.gov.pl/midas-web/pages/index.jsf? conversationContext=2 [Dostęp: 17 listopada 2018]

Piteau D. R., 1970. *Geological factors significant to the stability of slopes cut in rock*. [in:] Proc. South African Institute of Mining and Metallurgy, Symp. Planning Open Pit Mines, Johannesburg, 33-53.

Priest S. D., 1993. *The Collection and Analysis of Discontinuity Orientation Data for Engineering Design, with Examples*. [in:] Hudson J. A. (ed.) Comprehensive Rock Engineering. Principles, Practice & Projects. Pergamon Press, Oxford, New York, Seoul, Tokyo, 167-192.

Priest S. D., Hudson J. A., 1976. *Discontinuity Spacings in Rock*. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. 13, 135-148.

Riquelme A.J., Abellán A., Tomás R., 2015. *Discontinuity spacing analysis in rock masses using 3D point clouds*. Engineering Geology 195, 185-195.

Sousa L., Barabasch J., Stein K.J., Siegesmund S., 2017a. *Characterization and quality assessment of granitic building stone deposits: A case study of two different Portuguese granites*. Engineering Geology 221, 29-40.

Sousa L.M.O., Oliveira A.S., Alves I.M.C., 2017b. *Influence of fracture system on the exploitation of building stones: the case of the Mondim de Basto granite (north Portugal)*. Environmental Earth Sciences 75, 1, 1-16.

Stavropoulou M., 2014. *Discontinuity frequency and block volume distribution in rock masses*. International Journal of Rock Mechanics & Mining Sciences 65, 62-74.

Thiel K., 1989. *Rock Mechanics in Hydroengineering*. Developments in Geotechnical Engineering, vol. 51. Elsevier.

Wang H., Latham J.P., Poole A.B., 1991. *Predictions of block size distribution for quarrying*. Quarterly Journal of Engineering Geology 24, 91-99.

Xia L., Zheng Y., Yu Q., 2016. *Estimation of the REV size for blockiness of fractured rock masses*. Computer and Geotechnics 76, 83-92.

Znańska M., 1974. *Dokumentacja geologiczna złoża piaskowców krośnieńskich „Górka-Mucharz" w kat. B+C1, miejsc. Mucharz*. Dok. arch. Przedsiębiorstwo Geologiczne, Kraków