Environ Earth Sci (2011) 63:1911–1924
DOI 10.1007/s12665-010-0825-7

SPECIAL ISSUE

Optimized extraction of dimension stone blocks

S. Mosch · D. Nikolayew · O. Ewiak · S. Siegesmund

Received: 5 July 2010 / Accepted: 29 October 2010 / Published online: 30 November 2010

Abstract The profitable production of dimension stone mainly depends on the extractable block size. The regularity and volume of the blocks are of critical importance, and are controlled by the three-dimensional pattern of the discontinuity system. Therefore, optimization of block size has to be the aim when quarrying for natural stone. This is mainly connected to the quantification of joints and fractures, i.e., their spacing and orientation. The problem of finding unfractured blocks within arbitrarily oriented and distributed planes can be solved effectively by a numerical algorithm. The main effects of joint orientations on block sizes and shapes will be presented in this article. Quantification of unfractured blocks with the aim of optimization is illustrated by detailed studies on several quarries. The algorithm used in this study can be applied as a powerful tool in the planning of a quarry and the future exploitation of dimension stone. Application of the described approach is demonstrated on practical examples of quarrying natural stones, namely, sandstone, granite, rhyolite, etc. Block quarrying can be optimized by using the new 3D-BlockExpert approach. The quantification of unfractured rock masses is also shown to contribute to a more ecological protection and the sustainable use of natural resources.

Keywords Production of dimension stones · Joints and fractures · Block sizes · Optimization

S. Mosch (✉) · O. Ewiak · S. Siegesmund
Department of Structural Geology and Geodynamics,
Geoscience Center of the University of Göttingen,
Göttingen, Germany
e-mail: stephan.mosch@pigadi.com

D. Nikolayew
Frank Laboratory of Neutron Physics, Joint Institute
for Nuclear Research, Dubna, Moscow, Russia

Introduction

The term optimization implies improving a process that has specifically defined goals. For this, it is necessary to consider all the processes and modify them to achieve the best possible results. The main factors which increase the profitability of a dimension stone quarry are block size optimization and the focus on high quality raw materials as well as the avoidance of unnecessary waste and overburden. In this context the volumes as well as the geometry and the distribution of expected raw blocks is essential. Initial prediction of the relative part sizes will help to optimize the building stone production. Therefore, joints and fractures are among the most important geological structures, and its assessment is one of the most important tasks during exploration and the ongoing quarrying process.

The genesis of joint- and fracture-systems can be multifaceted and be traced back to orogenic, and epirogenic processes, as well as shrinkage caused by cooling or desiccation. As a discontinuity in a deposit, all surfaces such as faults, joints, cracks, fissures, or bedding planes has to be taken into account. The formation of separated individual blocks in a compact rock, the so-called in situ blocks (Lu and Latham 1999), is linked to the intersection of these discontinuities. Intrinsic structure characteristics such as quartz- or calcite-veins are also considered, if it can be foreseen that these vein tracings will open during further processing. Furthermore, the discontinuity system might impair the quality of a raw block even with mineralized fissures, since the individual décor of a rock can be interrupted.

Both the orientation and the respective distances of discontinuities have a significant influence on the prospective shapes and volumes of primary blocks. In general, wider distances result in large-sized blocks, if the orientation of discontinuities does not diverge decisively from orthogonality. When the geologic or tectonic situation results in acute and irregular blocks, a more cost-intensive and time-consuming process occurs, since these blocks must be resized to manageable dimensions for processing. If only one or more parameters, distances or dip angles are varying intensely, the extracted material can be utilized for low-value goods like gravel or paving stones (see Smith 1999).

Quarried raw blocks must generally meet certain criteria to fulfil the technical and economical requirements of a modern cutting inventory. The best conditions prevail if the raw block sizes range between 6 and 8 m^3 (Primavori 1999). The maximum dimension of the blocks conforms to the weight, when considering the safety issues of the transport and the handling of blocks during further processing. Minimum volumes for natural stone blocks determined for export are around 1–6 m^3, whereas standard dimensions range between 2.0 × 1.0 × 0.5 and 3.0 × 2.0 × 1.0 m (United Nations 1976). The dimensions of a raw block are also a significant factor for the processing with respect to the décor of a stone. While the width is finally responsible for the number of slabs that can be obtained from a block, its height and the length determine the size of each of those slabs. In this context, intensively decorated rocks that show e.g., folding, the broad side of a raw block has to show the corresponding décor.

In many deposits, however, ideal conditions do not prevail, so that blocks must be formatted to a processing-friendly geometry. A beneficial situation for dimensional stone mining is, for example, when the fragmentation into rectangular blocks is defined by a natural orthogonal fracture system. But in many cases, deposits of natural building stone are affected by a distinct variability of the orientation of joints, leading to irregular, often acute-angled blocks, whereby each block then needs individual cutting. In the Finnish granite industry, for example, the yield of sellable stone products ranges from 5 to 10% of the total volume of rock excavated (Prissang et al. 2007).

The problem of mutually orthogonal fracture patterns was considered by Weber et al. (2001) and Weber and Lepper (2002). More recent articles (Koch-Moeck and Germann 2007; Prissang et al. 2006, 2007) are also devoted to this problem. However, there is no general analytical solution, but for most three-dimensional cases an effective numerical solution will be presented in this article. The computer program 3D-BlockExpert developed in this study models the three-dimensional fragmentation of a deposit, based on the investigation of the tectonic elements, dip angles, and dip directions.

Methodological background

Data acquisition

Exact data acquisition is essential, both for the exploration of new deposits and the ongoing maintenance of active quarries. Consequently, the analysis of a discontinuity system in a deposit has to comprise the localization, mapping and evaluation of joints, bedding planes, fault zones, etc.

Data collection is based on different methods, which are adapted to the individual quarry situation. For further details of discontinuity analyses see e.g., Smith (1999), Priest (1993), Hoffmann and Siegesmund (2007a, b), or Mosch (2009). Furthermore, different geophysical methods are available such as Georadar. But the various methods usually require a higher technical and financial expenditure. Therefore, the mapping of joint space intervals can be done by making direct longitudinal measurements at the outcrop or in the quarry. The orientation of the joint surfaces is generally taken with a field compass. The fundamental problem is the recognition of the correct surfaces, where in some cases very fine crack structures only become visible after surface wetting.

In an ideal situation, the mapping of the joint system should be performed on vertical quarry walls. By the so-called "window sampling" or "scanline sampling technique" (ISRM 1978; Priest 1993), measuring lines have to be sited on the quarry wall in a vertical and horizontal orientation, enabling the acquisition of two joint sets (Fig. 1: wall 1, joint sets A, C). To create a complete picture of the joint system, another measurement needs to be taken at right angles to the previous wall (Fig. 1: wall 2, joint set B). A clear restriction that can appear is the termination behavior of the joint. Joints, whose strike can be

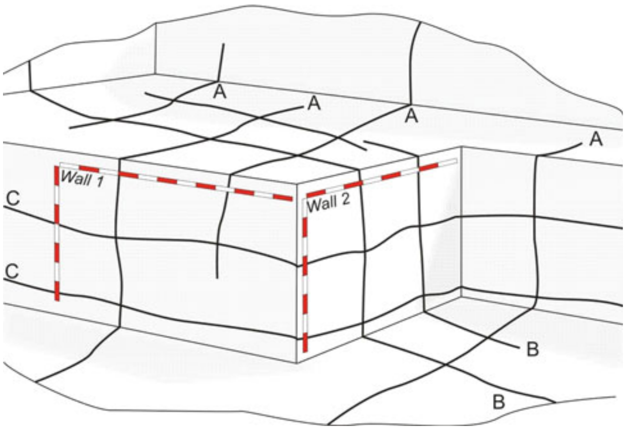


Fig. 1 Representative sketch in an area designated for excavation showing the vertical and horizontal measuring lines on two quarry walls intersecting joint sets *A*, *B*, and *C*

followed along a section of the wall, can disappear after a few centimeters into the depth of the rock and completely discontinue or change orientation. Thus, the "window sampling" may either register too small or too large distances between the joints. For assessing the area of the rock to be excavated, it may be useful to thoroughly clean the rock body, so that the traces of the joints in the wall can be followed. This would complete the overall three-dimensional picture of the rock body under consideration for excavation.

Representation and application possibilities

The use of isoline diagrams like Schmidt Nets to depict data obtained from the mapping of discontinuities like joints and joint sets in oriented space has proven to be a valuable tool. Figure 2 shows the orientation of different joint and fracture systems developed in the same quarry. In Fig. 2c, two steep joint sets are visible whose strike direction is almost perpendicular to each other. This joint system results in an almost uniform dissection of the rock body exhibiting relatively rectangular blocks. The fracture system shown in Fig. 2d also exhibits a preferred orientation, but joints striking in an E–W direction exhibit a stronger variation. Here a third joint system is developed leading to a stronger dissection of the rock body. Overall the quarry shows a considerable heterogeneous distribution of joints, where some aspects show a stronger fragmentation of the rocks.

Evaluating the data by the use of histograms is a good way of representing the frequency distributions of the distances between joints (see Singewald 1992). Simultaneously, when taking the mean of the joint distances into consideration, the volume calculation of a so-called average block ($\overline{x} \cdot \overline{y} \cdot \overline{z} = \overline{V}$; Singewald 1992) is possible. When making a general assessment of a deposit, this parameter is especially applicable in the area of sedimentary stratiform deposits. If the joint structure deviates from an orthogonal geometry, or if one or more joint sets show a pronounced scattering, then only estimations can be made whether a specific domain in the quarry is suitable for the excavation of raw blocks. The quarry section showing a greater variation in the strike and dip of the joints exhibits a tighter joint spacing (Fig. 2e, f). Thus, it is more suitable for excavation of crushed rock. The tight joint system becomes really evident when the spacing is measured along a horizontal line. Along a measuring distance of 30 m, 60% of the joint intervals are below 0.5 m. Consequently, a complete inspection of the orientation and joint space distribution is possible within the discontinuity structure, and by evaluating the general degree of dissection in a rock body make estimates for the excavation of stone blocks.

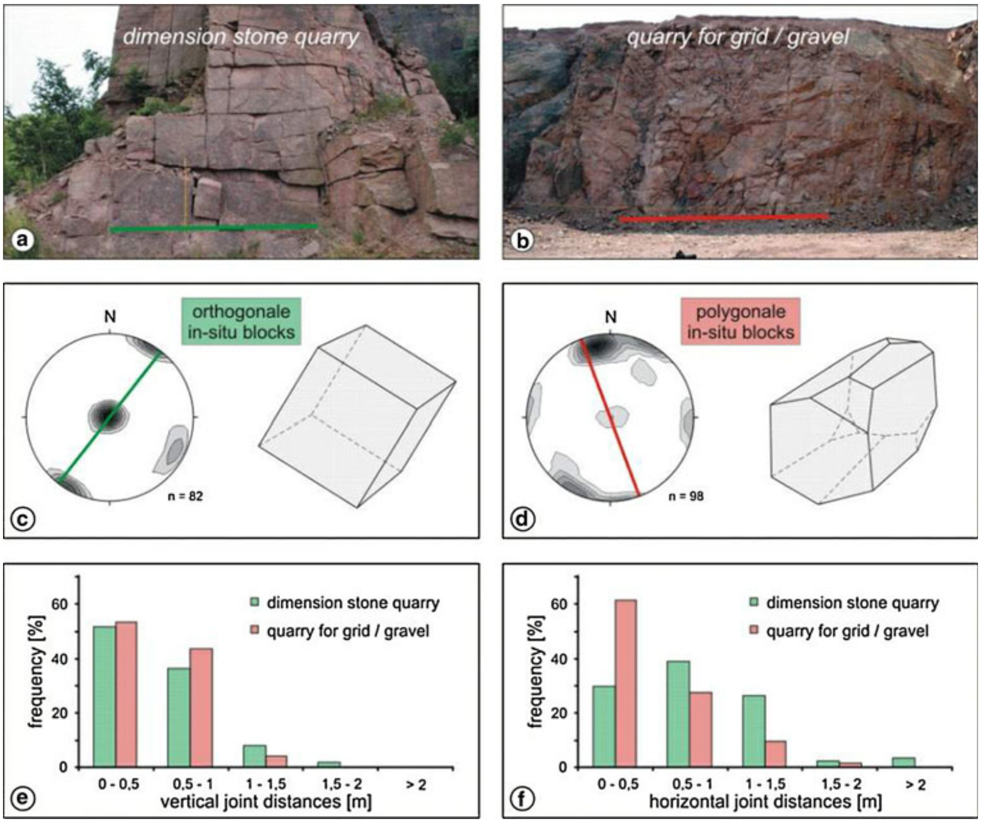


Fig. 2 Quarry sections of the Löbejüner Qtz-Porphyry (Germany): **a** in-active dimension stone quarry and **b** active quarry for grit and gravel. Density distribution diagrams (**c**, **d**) depict the orientation of joints leading to the expected shapes of in situ blocks (*green* and *red line* equals the orientation of each quarry wall). The distribution of joint distances (**e**, **f**) shows a stronger fragmentation in the quarry for grit and gravel

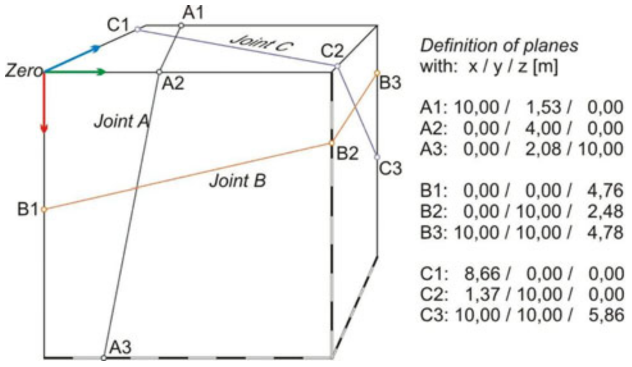


Fig. 3 Characteristic data input for the software 3D-BlockExpert for describing joint planes using three points localized in a coordinate system (after Mosch 2009)

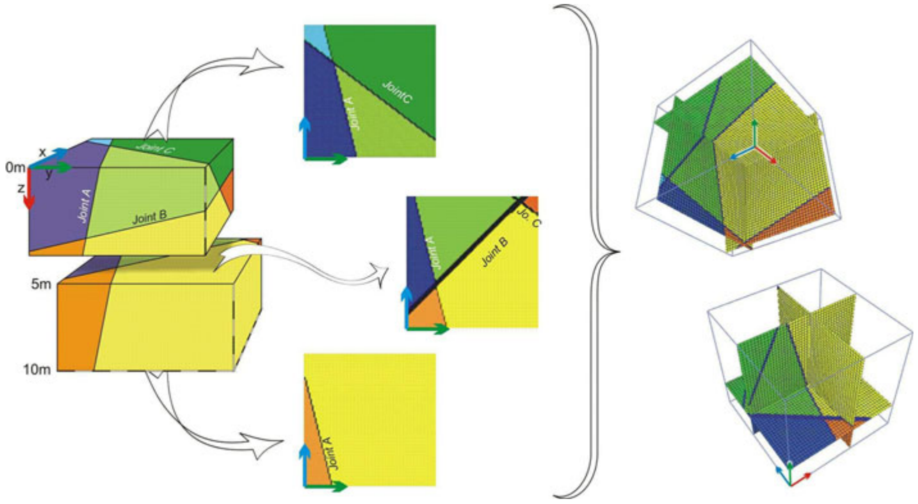
The software 3D-BlockExpert

To visualize the fragmentation of a rock body due to its segmentation by discontinuities, the software known as 3D-BlockExpert has been developed (Nikolayew et al. 2007; Siegesmund et al. 2007; Mosch et al. 2009). The computer program is able to evaluate data on the spatial distribution of joints and provides information dealing with the distribution of in situ blocks, as well as their volumes and shapes. A joint is considered to be a plane, which can be described mathematically with three points localized in a coordinate system (Fig. 3). The necessary measurements can easily be carried out in a quarry or in the early stage of exploration, following the “window sampling” or “scan-line sampling technique” (ISRM 1978; Priest 1993). The software regards the treated area of a quarry as being a parallelepiped, i.e., a geometric body composed of three pairs of parallelograms, each pair in two parallel layers. The body is divided into cells or voxels (volumetric pixel) of the same size. Due to the integration of primary data into this mathematical model, the description of its three-dimensional segmentation is possible. An iterative process, which is based on a numerical algorithm, assigns one color to these voxels that build up one singular in situ block. After the tessellation is modelled, the volumes of each region can be easily calculated.

Based on this mathematical modelling, the software can create two-dimensional sections parallel to each surface of the treated rock body as a first step in evaluating a quarry (Fig. 4). The number of sections for each direction depends on the chosen number of voxels. Simultaneously, the voxel size defines the resolution of the created model. Field studies have shown that a resolution of 12 cm (edge length of one voxel) is sufficient to describe natural joint or fracture planes for the goal of dimension stone quarrying. For practical purposes, it can be argued that this is a more adequate description than in the case of a mathematical object such as planes, which have zero volume. Moreover, computing time is very closely connected to the size or number of voxels under consideration. The time increases as a cube to voxel edge length. So, for primary evaluation and volume estimation in the field, a small number of voxels is preferred.

Besides these two-dimensional sections the program creates a data set, which can be translated into a three-dimensional model. Moreover, with the software Intel® Array Viewer a multivariable modelling of the segmented body with a free choice of section as well as a free rotation of the whole model can be viewed in all directions of space (Fig. 4). Thus, the user is able to examine the quarry situation from all possible perspectives, and also to get an idea about the distribution of in situ blocks and to estimate its shapes.

Fig. 4 Possible outcomes for 3D-BlockExpert showing two-dimensional sections (*middle*) as well as three-dimensional models (*right side*) of a characteristic block (compare with Fig. 3)



Results of modelling with 3D-BlockExpert

Field study: Löbejüner Qtz-Porphyry, Rhyolite, Germany

This example deals with the Löbejüner Qtz-Porphyry, a rhyolite body near Halle (Saale) in Saxony-Anhalt (Germany). The rock mass is partly quarried for dimension blocks. Generally, the quarry is characterized by a joint system, which clearly shows visible changes in relatively short distances (compare with Fig. 2). The variations include orientation changes, varying numbers of joint sets, and variations in spacing. The examined former quarrying area is characterized by a joint system, which consists of three main joint sets. The first set is comprised of (sub-) horizontal joints cutting the rock at an average spacing of 0.52 ± 0.31 m. These planes usually are irregular or undulating. The other two sets roughly strike NNE and ESE. They are characterized by steep dipping planes, which show a large continuity in parts but can also be restricted to individual layers. The sets intersect each other at roughly 90° and show an average spacing of 0.82 ± 0.54 m. The roughly orthogonal character of the joint system causes more or less rectangular in situ block shapes. However, the low spacing and high joint density causes relatively small block volumes. Based on the spacing distribution and the approach of Palmström (1995) an average block volume of 0.4 m^3 has been calculated. The average joint density in the examined rock mass is as high as 4.3 joints per m^3 and thus, according to Sousa (2010), too high for the exploitation of large volume blocks.

For this reason, it is highly important to locate areas with lower joint density, and thus higher block volumes. For modelling the joint system with 3D-BlockExpert a body of 7 × 6 × 4 m was chosen (Fig. 5). After data acquisition in the field, the first steps were reconstructing the joint pattern and defining the planes for the model input file. The voxel size chosen for the model was 12.5 cm in each direction, so one voxel corresponds to a volume of roughly 2 dm^3. The model comprises 20 joints, which were partly constructed based on orientation measurements and geometric extrapolation.

The resulting model shows a partly orthogonal character of the joint system, although some joint planes show orientation deviations (Fig. 6). For this reason, the modelled rock mass comprises a small number of in situ blocks with an acute-angled shape as well. Based on the model, the average volume of the blocks is roughly 0.5 m^3 after removing the voxels attributed to joint planes and little rock volumes <100 voxels, which matches the theoretically calculated average. The largest blocks in the modelled rock mass have a volume >2 m^3 and are located on the SSW side of the rock mass. Summarizing, the relatively small block volumes and the partly non-orthogonal geometry, which would cause material losses during formatting of dimension blocks, disqualify the rock mass for quarrying of large dimension blocks. Due to the low spacing in all three joint sets, there is no way of optimizing the yield in this case.

Field study: Bucher Sandstone, Germany

Massive sandstone deposits are characterized frequently by a more or less orthogonal joint pattern. In some quarries the joint system enables the extraction of orthogonal raw blocks without using e.g., drilling machines or explosives. For dimension stone purposes a more complicated situation is given in the deposit of the fine- to medium-grained Bucher Sandstone. Here the joint pattern is characterized by at least two different sets of joints. One is clearly N–S striking with dip angles of more than 80° (Fig. 7). These steeply dipping joints are cut by a second set of joints, which show a higher variability in both, first of all strike as well as dip angle. In the actual quarry situation there was a lack of subhorizontal joints. Only in the upper part one can see single joints with estimated dip angles of around 10°–15°. In total the rock body exhibits a heterogeneous

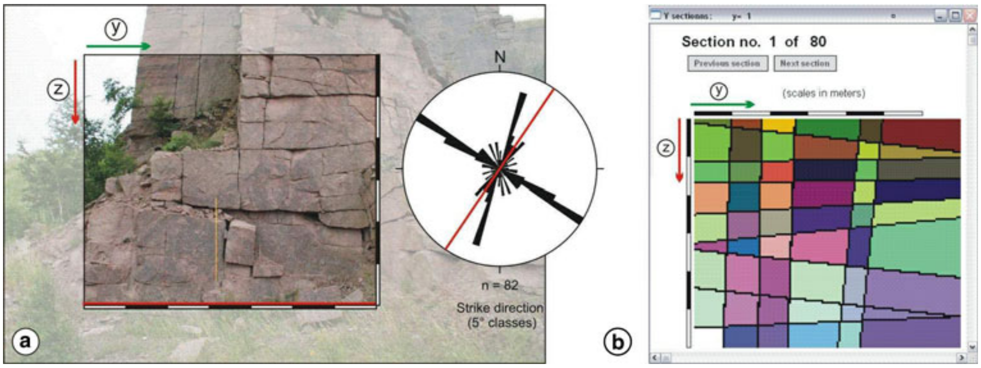


Fig. 5 **a** In-active quarry section of the Löbejüner Qtz-Porphyry (rhyolite; Germany): the joint pattern is characterized by a more or less homogeneous and orthogonal orientation of joint sets (compare with Fig. 2). **b** Two-dimensional front view of the quarry section in **a** modelled with 3D-BlockExpert

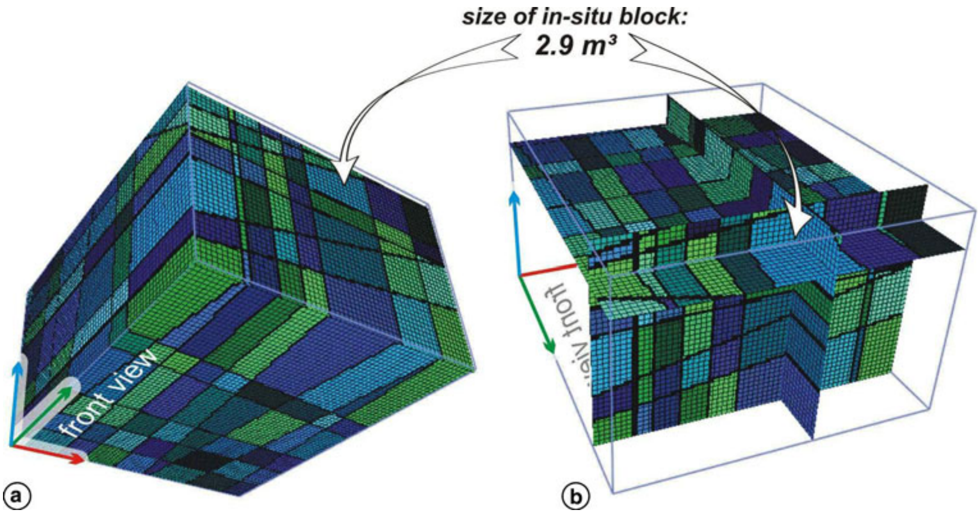


Fig. 6 **a** Three-dimensional model of the quarry section of the Löbejüner Qtz-Porphyry shown in Fig. 5. **b** Due to the multifaceted possibilities of rotation and section choice, the largest in situ block can be detected in the lower right back part of the treated rock mass

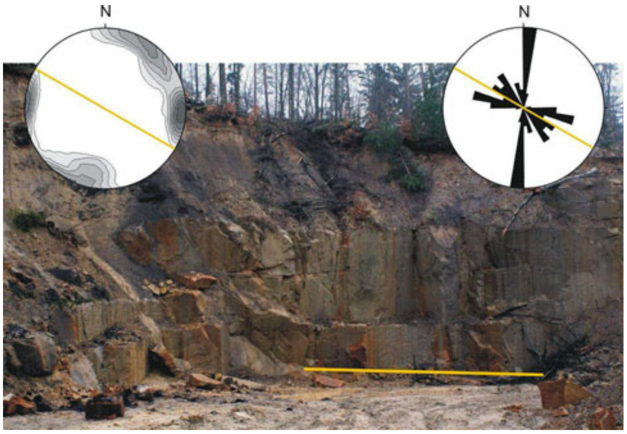


Fig. 7 Quarry of Bucher Sandstone (Germany): the joint analyses show that an N–S striking and steep dipping system of joints is cut by a more heterogeneous set of joints

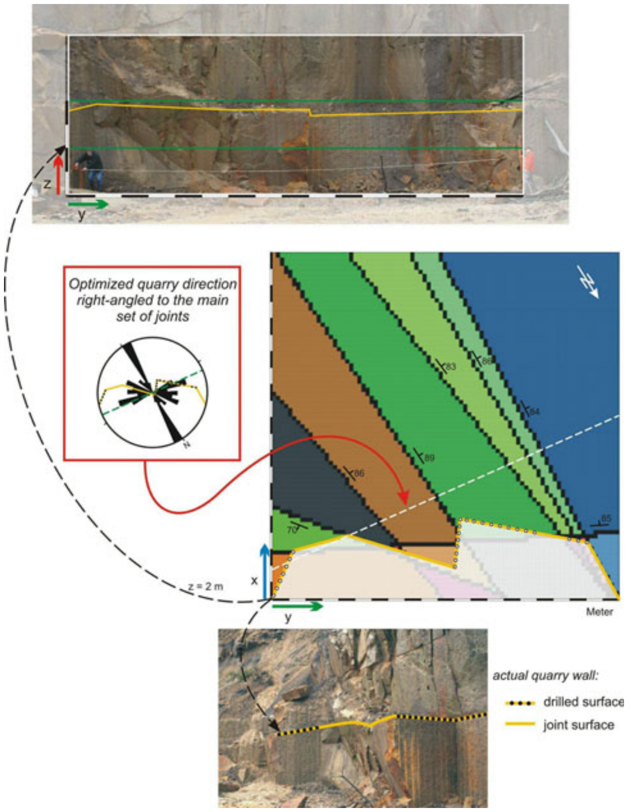


Fig. 8 Quarry of Bucher Sandstone (Germany): modelled section of a possible quarry bottom, which can be expected with an ongoing extraction process. An additional fragmentation of in situ blocks is clearly visible in detail due to the use of drilling machines. To fit the quarry direction to the best possible joint pattern, a suitable rotation should be carried out

fragmentation, which leads to problems in the extraction process.

In detail it becomes clear, that the actual wall of the quarry does not really fit the orientation of the joint pattern, which can be easily shown by using two-dimensional sections modelled with 3D-BlockExpert. For this reason a segment of the actual wall was determined in detail (Fig. 8). Here, the traces of the drilling processes are clearly visible showing an additional but avoidable fragmentation of the in situ blocks. The direction of the excavation front must be changed to optimize the dimensional stone to waste rock ratio.

The quarry was examined a second time. The general joint pattern for a newly opened of the quarry is more or less similar to the previous observation. The strike of the main joints has rotated only a few degrees in an E–W direction and the more heterogeneous sets of joints is less distinct. Due to the removal of the sedimentary covering (compare with Fig. 7), it was possible to collect data concerning the joint distribution in all directions of space, which could be brought together into a three-dimensional model (Fig. 9). In connection with the two-dimensional section of the expected quarry bottom, it becomes clear that especially the southern part of the treated body exhibits a

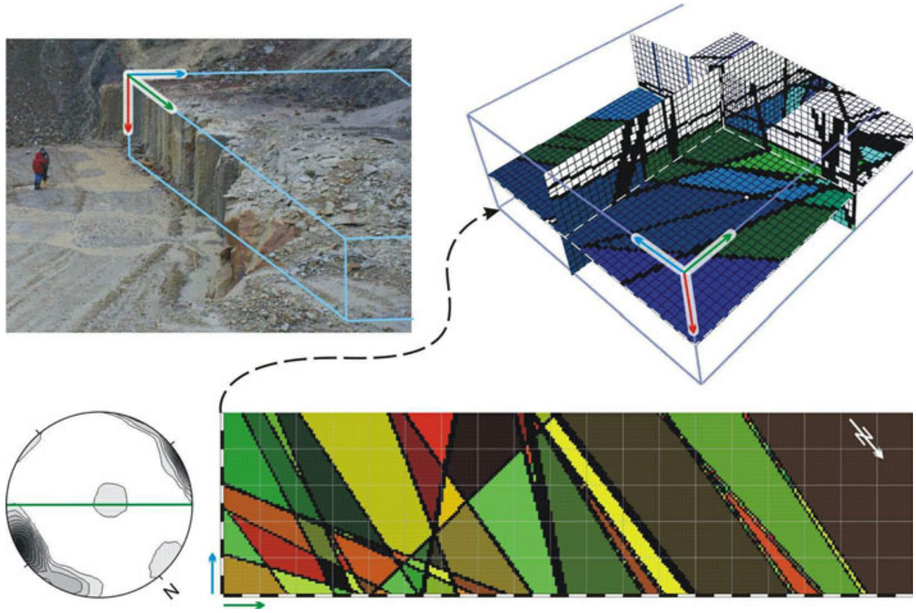


Fig. 9 Quarry of Bucher Sandstone (Germany): characteristic three-dimensional model of the *upper section* of the quarry showing the heterogeneous fragmentation of the treated block in the southern part. The two-dimensional section of the expected quarry bottom parallel to the actual quarry wall explains the need for changing the excavation front

strong and heterogeneous fragmentation. Moreover, this part is also cross-cut by two distinct subhorizontal joints, which were described above. However, the actual wall mainly shows drilled surfaces. To summarize, the change of the extraction front can lead to a greater exploitation of raw blocks.

Modelling for optimization of final block cutting

Rock bodies that are essentially compact, homogeneous and have widely spaced joints show similar possibilities for optimization. This only occurs when a few discontinuities like distinctly colored veins or similar irregular structures are present. If these elements do not conform to the characteristic rock ornamentation, a significant amount of material loss can result, which may continue up to the cutting of the raw block (Fig. 10).

Figure 11 shows a schematic representation of a quarry that is pervaded by such bands. In this situation the placement depth of the slab can have a positive impact on the amount of waste material produced. The rotation corresponds to the longitudinal axis of the raw block. The theoretically usable parts of the raw blocks are compared, which is given by the bearing of the longitudinal axis at right angles to the excavation direction (Fig. 11a), and parallel to the excavation direction (Fig. 11b) for the following extraction steps. In the second case, the length of the raw block is defined by the size of the extracted slab. Hence, the maneuverability is the solely limiting factor for the detached sections. To counteract this, a reduction in the terrace height should be done.

At this point sections parallel to the extraction front can be helpful. The respective sections are chosen in such a way that the front and backside of the potential slab can be rendered, where the thickness represents a dimension in the final raw block. The form of the resulting in situ blocks can be constructed from these simple geometric relationships, whereby the primary rock waste can be estimated from the

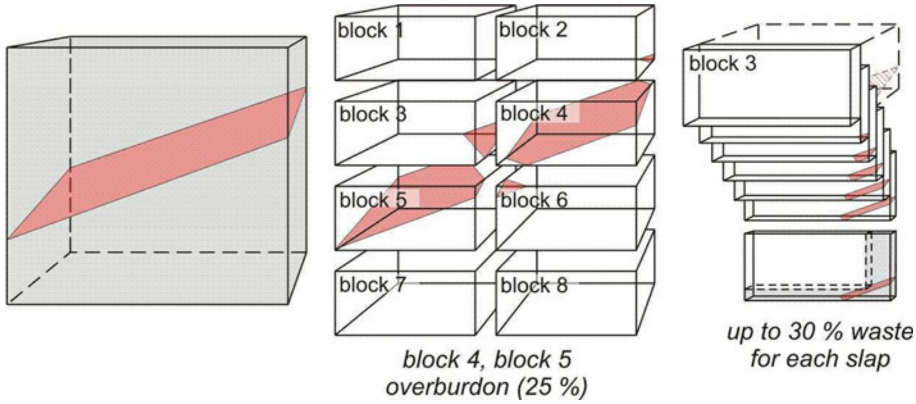


Fig. 10 Theoretical waste material resulting from the formatting and cutting of raw blocks from a simple cleaved slab

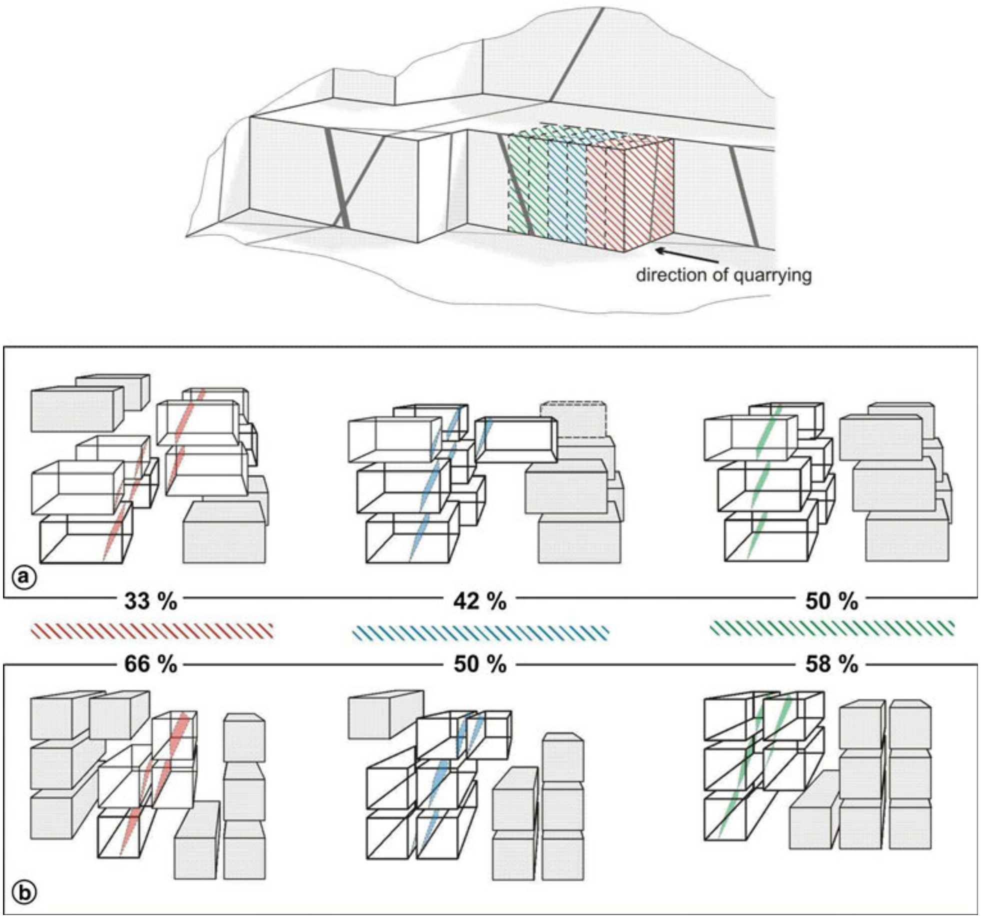


Fig. 11 Schematic representation of a homogenous and compact rock body that is pervaded by a few irregular discontinuities. Adjusting the size of the extracted slabs and the arrangement of the recovered raw blocks can have a positive effect on the quality of the stone-waste material balance. Different colors designate the excavation direction for the following successive steps. Orientation of the longitudinal side of the raw block: **a** in the excavation direction and **b** at right angles to the excavation direction. The fraction of completely usable raw blocks is given in *percent*

resulting perpendicular parting of the side surfaces. As a consequence, it is possible to fill in the best surface area utilization with regards to the actual usable material in two dimensions.

In Fig. 12 such an optimization of formatting a raw block is depicted. From a multitude of possibilities three examples are singled out. However, it becomes clear that a corresponding displacement of the arranged raw blocks as well as the possible number can also influence the necessary cutting work. Economic factors also have to be taken into consideration. The highest block number can be realized with arrangement possibility C. However, the formatting is connected to a very high labor input (relative cutting length) in contrast to the arrangement possibility B. In this case, the expected price segment of the rock has to be taken into account, and the additional earnings have to be balanced against the cost overruns for production. Through a corresponding evaluation of successively extracted slabs, additional prognostic information can be obtained concerning the number and volume of raw blocks in the excavating section. Besides the direct planning of excavation, the process can be viewed as a tool, where for example, further steps of manufacture are planned or the requirements of the market can be aimed for. The prerequisite for such an optimal utilization is that the regarded area is free of defects. Areas that show, for example, a clear change in color or something similar have to be excluded, especially when the stone does not meet the defined standards. One problem that can occur is when rock varieties contain ornamentations defined by specific structural elements, and thus requires a particular orientation of the raw block in the extracted slab.

Discussion

The goal in the excavation of dimension stones is to produce rectangular-shaped raw blocks for further use in the stone industry. In many cases, it is not possible to extract such corresponding blocks with the requisite perpendicularity because of deviations in the joint system. This is why a worldwide average of around 50% (Montani 2003) overburden is produced from the excavation and formatting of the in situ blocks. Frequently this value lies much

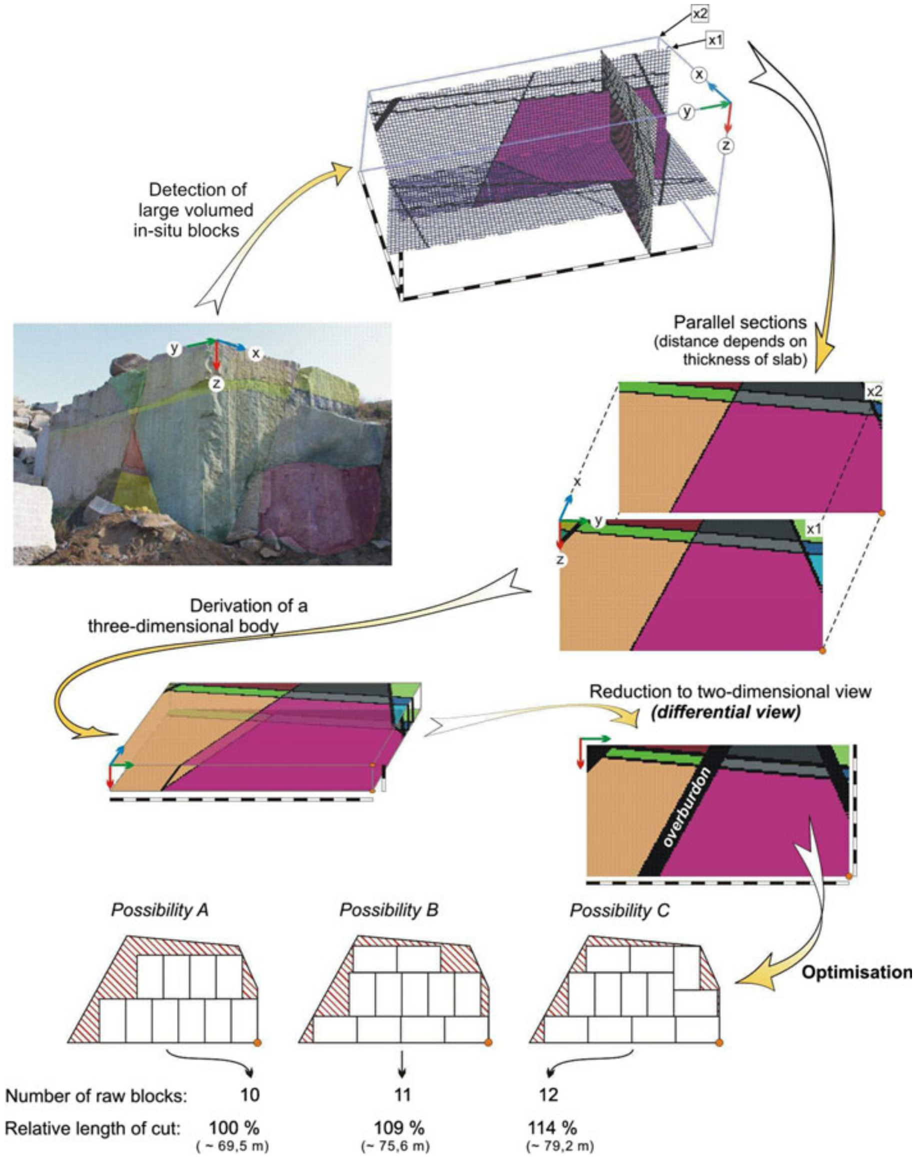


Fig. 12 Detection of large volume in situ blocks and the optimization of raw block production (block size: 3 × 2 × 1.8 m) by utilizing the model generated with data from the joint system analysis in the software 3D-BlockExpert. For optimal surface area utilization three examples from a large number of possibilities are presented (granite; San Antonio, Sardinia)

higher, whereby the demand for the quality of a rock and its marketability or rather its premium price segment takes precedence. When removal rates of 80% or more occur in excavating gray colored granites, for example, the profitability of a deposit must be called into question.

The model in Fig. 13 shows in an exemplary way how changes in a system of orthogonal discontinuities occur, when accompanied by a rotation in one or both joint system groups. A comparison of the joint spacing distribution leads to the same results in all the three cases. Furthermore, an increase in material loss occurs, and that a simultaneous decrease in the average block size can be documented (Mosch 2009). Excavating a dissected stone deposit in this way leads to lower earnings, which has been demonstrated by a comparative evaluation in magmatic deposits from Thailand (Hoffmann and Siegesmund 2007a, b).

Stone deposits are a complex three-dimensional rock body, and the model presented above deviates from a natural example. This means that an orientation of the joints, such as those illustrated in Fig. 13 may only be aligned vertically with exception in some cases. Thus, a further decrease in the production rate results, based upon the angular deviation of the defined planes in an in situ block.

The impact of the angular deviations described above becomes very apparent in the Negro Grapesa qtz-bt diorite quarry in Spain (Fig. 14a). The rose diagram (Fig. 14b) shows a relatively heterogeneously strike distribution of the joints. Two distinct preferred orientations can be distinguished that dissect each other at an angle between 60° and 70° (Fig. 14c). The excavation wall or floor of the quarry only follows to a minor degree the general trend of

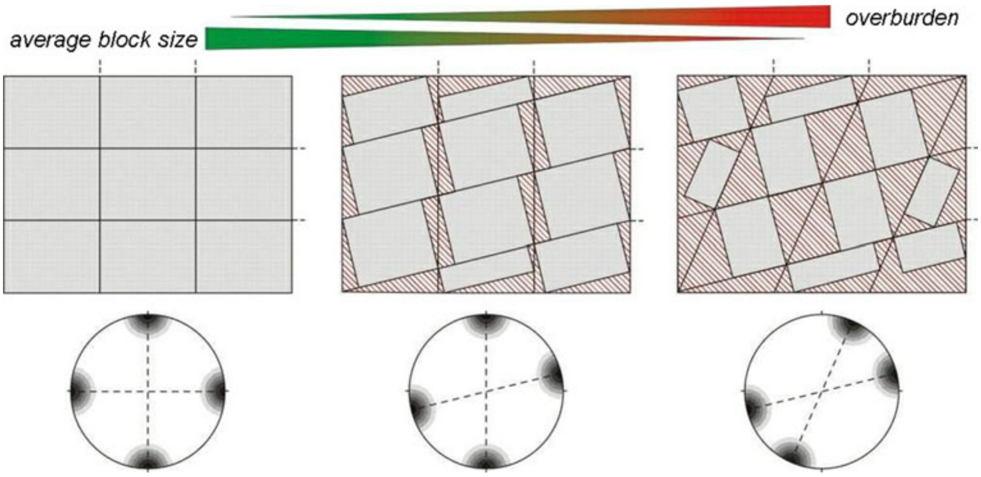


Fig. 13 Increase of cutting (overburden) remains with decreasing average block size due to the joint system deviating from orthogonality where the spacing pattern remains equal. The characteristic joint density distributions depict the orientations of each joint pattern

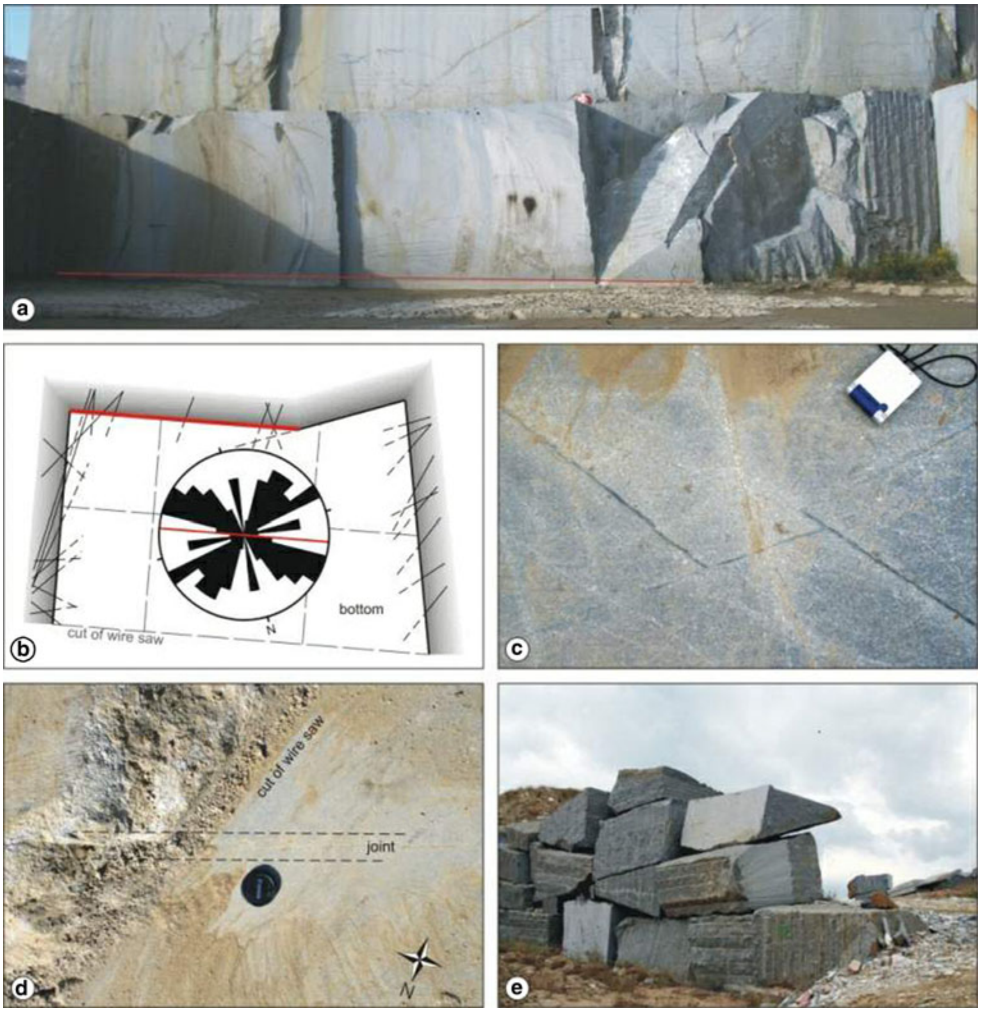


Fig. 14 Impact of a non-orthogonal joint structure: **a** quarry of commercial grade Negro Grapesa (qtz-bt-diorite, Spain), **b** excavation horizon with accompanying joint orientation rose diagram and sketch depicting the measured joints (*black line*) as well as the wire-cut sections, **c** acute-angled cutting of joints on the excavating horizon, **d** executed cut at an acute angle to the NE–SW striking joint, and **e** mine tailings with a large number of non-rectangular leftover blocks. See text for explanation

the joints, which is probably due to the heterogeneity of their distribution. Many parts of the quarry walls show small and large scale outbursts at the corner intersections as a result of this heterogeneity. Moreover, between the joint planes and the cutting direction acute angles are observable (Fig. 14d). As a consequence, the overburden contains many acute-angled leftover pieces, which are produced by the drilling of the in situ blocks (Fig. 14e). For block excavation it is essential that stone deposits exhibit an appropriate distribution of joints, when at least one direction of a natural joint surface in a rock can be utilized for production.

Another aspect for dimension stone utilization is the homogeneity of the joint surfaces and their distribution, along with the distribution of the joint spaces and the orientation of the discontinuities. Marbles or other metamorphic rock deposits are especially characterized by heterogeneous joint. Figure 15 shows an example of the joint distribution at the excavation wall in a quarry from the Spanish marble province Macael (Mosch 2009). In this quarry section, joints with two main strike directions are recognized (Fig. 15b). The joint structure almost matches the orientation of the quarry wall. However, the presence of acute angularity is also a problem. Due to strong fluctuations in the dips of the joints, the output for well-dimensioned raw blocks with a specified form is considerably diminished. The dips show a relatively even distribution and cover a spectrum ranging from 5° to 88°. The entire NNE–SSW striking joint system shows a small variation in the dip and must be placed somewhat steeper. Because of the excavation wall orientation and the strong dip variation in the joint sets that are hardly observable, an estimation of the possible quarry output is strongly limited. In this case, an additional wall parallel the NW–SE striking joint system would have to be made accessible.

When considerable deviations occur in the orthogonal structure or the joints show strongly fluctuating dip directions, applying histograms should be done with caution for the assessment of the joint spacing distribution. Especially in this case, the choice of the measuring line can have an influence on the relative frequency distribution (Fig. 15a). This can also result in deviations when calculating the average volume of a block (Mosch 2009).

In general, the results from a discontinuity analysis may show certain variations dependent on the lithology or the tectonic conditions. In sandstones, for example, a phenomenon that frequently occurs is a wave-like course of the bedding, which results in strong changes in the bedding thickness. Similar observations can be seen in the joints of granitic rock bodies. Thus, caution is required when making an assessment of the joint spacing distribution.

Through a heterogeneous formation of the joint structure, however, it becomes clear that a two-dimensional section of a deposit has limited significance when it is based solely on the distribution of joint spaces. Another example where the complexity of the joint system and its impact to the economical value of a deposit are clearly visible is the quarry La Cantera Kinzigita in Argentina (Fig. 16a, Mosch 2009). This quarry is dedicated to the extraction of Azul Tango, a cdr-gt gneiss. When regarding the fracture system, both the strike direction and dipping angles of the joint and fracture planes show an obvious variability. The density distribution of the orientation data shows a preferred E–W strike direction and steeply dipping joint planes (Fig. 16b). In spite of a larger variation in strike, two main joint sets could be identified. These sets intersect each other at angles between 60° and 70°. The spacing data display a closely spaced joint system with an average spacing of about 1 m in all spatial directions (Fig. 16c). Based on the joint spacing, an average block volume of approximately 0.9 m^3 has been calculated. From all the data an extensive and unsteady joint and fracture system has been deduced. The heterogeneous character of the joint system finally led to the closing of the quarry.

Both exploitation and formatting of dimension blocks has been achieved by the use of drillings and explosives. The examination of several parts of the stopping levels showed that the quarrying strategy has been poorly or even not at all adjusted to the local geological conditions. Without regarding the local joint system, the vertical

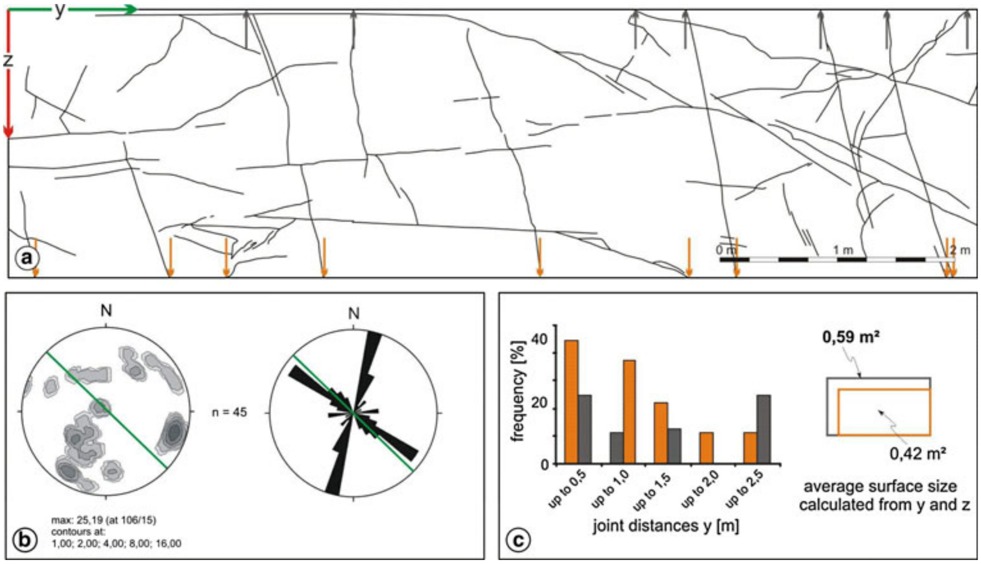


Fig. 15 **a** Sketch of the joint system pattern on a quarry wall (Blanco Macael, marble, Spain), **b** diagrams depicting the joint distribution in the above quarry, and **c** joint space mapping along various traverses (*orange-below*, *grey-above*, corresponding to the sketch in **a** that result in different average surface measurements. See text for explanation

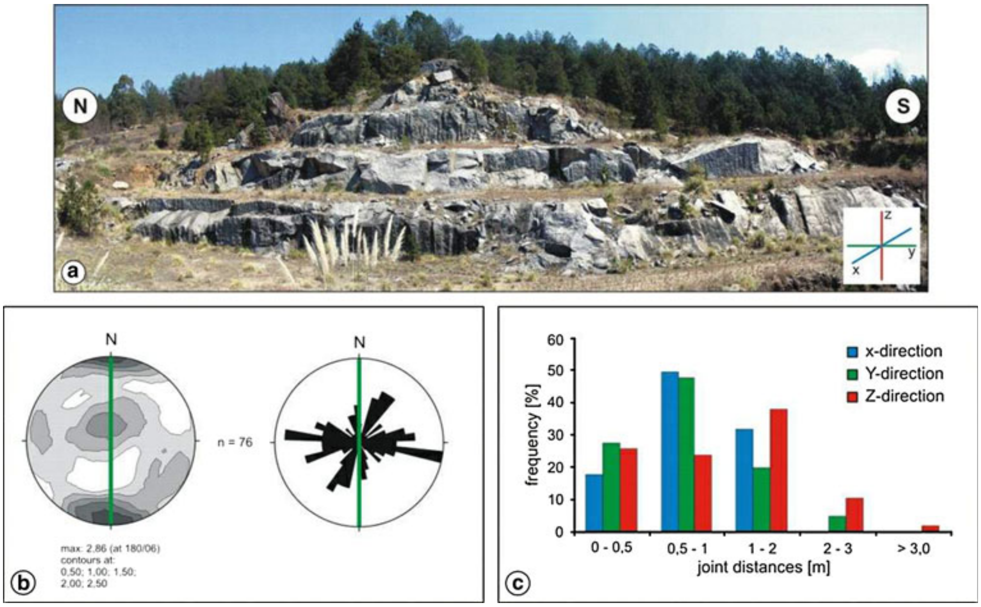


Fig. 16 **a** Quarry "La Cantera Kinzigita" (Azul Tango, cdr-gt-gneiss, Province of Córdoba, Argentina). The **b** orientation data and **c** the spacing data depict a closely spaced joint system without a preferred orientation

drillings broke through joint faces and possibly damaged large-sized in situ blocks. Damages have been visible on many raw dimension blocks in the stock. Defects ranged from healed joints to open joint planes or grave deviations from orthogonal geometries. In spite of this, the yield has been about 10–20%.

The more reasonable way would have been a selective exploitation concentrating on individual large volume blocks. A basic prerequisite for this would have been the recognition of the preferred joint orientation and the parallel adjustment of the exploitation faces to the main strike direction (approximately 100°–280°). In addition, all faces should have been cleared of waste to allow for a better overview of the run of joints and fractures. Each quarrying step should have been planned according to the characteristics of the joint system, which requires a constant detailed analysis of the joint and fracture system to locate individual large volume blocks in the rock mass. These blocks should be uncovered gently by using the existent joints of the rock mass. Regarding the high quality and value of the material, a higher amount of waste material connected to the extraction of defect-free large volume blocks could have been eventually acceptable.

Excavation of dimension stones can be achieved, however, when an ideal coordination of the mining procedure takes the elements of the joint system structure into account. This situation has been ideally implemented in the Bärenburg Quarry (Switzerland) by the extraction of the commercial grade Verde Andeer (Fig. 17). In this gneiss complex, two main joint sets occur next to horizontally aligned joints (joint set A), which are not represented in the discontinuity analysis due to the distinct orientation and equally spaced joint intervals. This is an ENE striking joint system with some dips reaching greater than 80° (joint set B), as well as being frequently healed by tourmaline mineralization (Fig. 17b). Overall these healed joints are of low stability, whereby potential joints can open during the process of excavation. This healed joint system is cut along strike by another approximately 90° joint set C, whose average dip is about 50° to the NNW. Like the horizontal joints, these joints exhibit a low mechanical coherence, and can be detached by the use of a few drill holes at intervals of around 1.5 m and the gentle application of well-placed explosive charges. In general, this produces a joint structure in which two main joint sets are almost perpendicular to each other (joint sets A and B), and a diagonal system (joint set C) that cuts both.

The first step of an extraction is completed by the placement of tightly spaced core holes, which are drilled perpendicular to the diagonal joint. Only one layer is drilled through. In the second step, joint set C will be pried open along the mapped part of the quarry at a length of around 40 m. At the same time the mineralized joints of joint set B can open. The mining floor is defined by the horizontal bedding joints (joint set B). This produces non-rectangular formats in the in situ blocks, which then has a part of the waste material removed creating a squaring of the block. Based on the tectonic conditions in the Bärenburg Quarry, this can not be avoided by a change in the mining procedure.

Summary

The complexity of a joint system can clearly generate problems concerning the opening of a quarry and defining

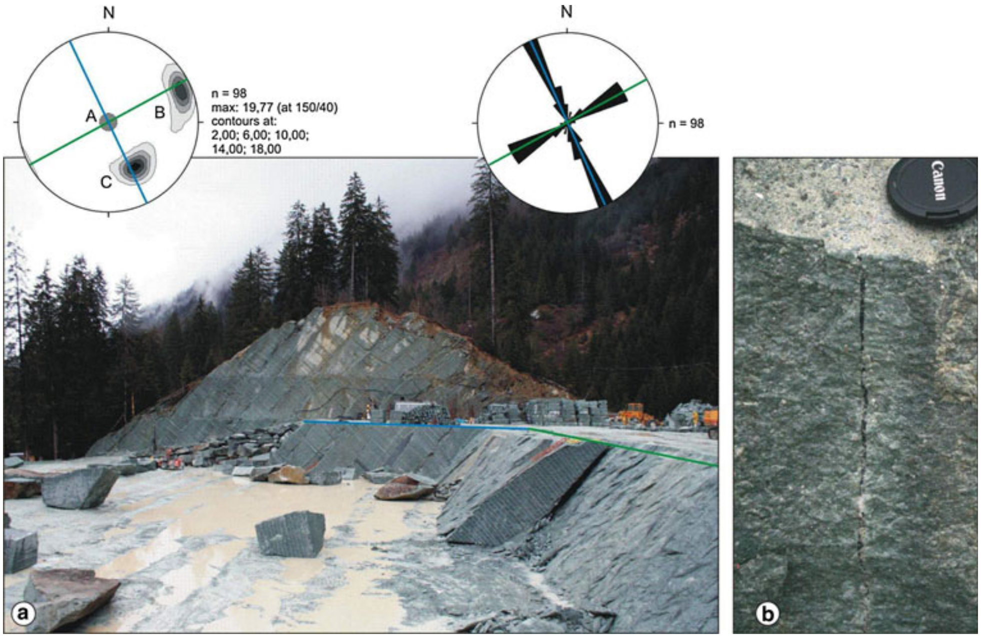


Fig. 17 Quarrying of the Verde Andeer Orthogneiss (Switzerland): **a** joint distribution in the eastern part of the Bärenburg Quarry (Toscano AG) and **b** joints healed by tourmaline mineralization acting as potential fractures. See text for further information

the direction of ongoing mining (Primavori 1999). Hence, the new approach to characterize and quantify unfractured rock masses for optimization of its use for dimension stone production is an outstanding method for the processing of joints in all spatial orientations. And furthermore, as a means for depicting two- and three-dimensional representations of a dissected rock body, which is based upon detailed mapping of the discontinuity system. The respective volume of the in situ blocks can be calculated simultaneously with the modelling of the stone deposit as well as estimating the resulting geometries. The best possible course for the quarrying is when the extraction is aligned with the joints, so that unnecessary cuts do not cause a further dissection of the rock body. Thus, it is possible to detect areas that are not minable, whereby greater amounts of waste material can be avoided.

In terms of profitability of a dimension stone quarry, the arrangement at the extraction wall is of importance for directly adapting the planning steps at the running excavation site. This is significant for the slab thickness or the quarry wall height, which is dependent on the given geological as well as tectonic relationships in a deposit. Using the natural breakage of the stone lowers the time-consuming and cost-intensive process of splitting the stone by drilling or saw cutting. Even this aspect can be achieved with the new approach by using the software 3D-BlockExpert when considering the possible extraction variations. The so-called differential view of the two sections describes the spatial construction of a potential slab as seen in a two-dimensional representation. Cutting planes with a specific spacing are chosen that describe the front and back of the extracted slab, which are made to match the final dimensions of the raw block. The actual exploitable material can be quantified by the removal of the overburden when drilling perpendicular to the wedge faces. Afterward the remaining quality stone can be filled out (in two dimensions) with respect to the best computer-assisted surface exploitation. In the optimization example, three excellent cases are singled out from a wide variety of possibilities. However, a dislocation in the arrangement of the blocks can clearly influence the possible number of raw blocks as well as the necessary cutting work. At the same time careful consideration has to be given to the economic factors. The highest block number can be realized by arrangement C, however, the formatting is connected to a higher labor input (cutting length). In such a case the consideration between more production costs and possible increased profits is mandatory. By evaluating the succession of extracted slabs, additional predictions can be made in regards to the number and volume of raw blocks that can be produced in future locations from the quarry. With the support of the actual excavation plan a tool can be developed, whereby further steps in the manufacturing process are planned, or selective extraction is done in reaction to the needs of the market.

In summary, a systematic and detailed map of the joint structure in a quarry enables one to:

- estimate the possible uses of the stone deposit
- detect areas which are not suitable for use and concentrate on areas where high quality resources occur
- optimize and adapt the extraction process
- and optimize the formatting process of the raw blocks.

By paying attention to the spacing distribution and the orientation of the joints that occur one can:

- achieve a positive influence between the relationship of the overburden to the usable stone
- optimize the block exploitation, and thus, positively influence the profitability of the quarry
- and increase the effective production and utilization of the natural stone resources.

In addition to the economic components, unnecessary environmental damages that accompany an uncontrolled exploitation or the effects of expanding the quarry can be avoided. Therefore, a contribution can be made toward ecological protection and the sustainable use of natural resources.

References

Hoffmann A, Siegesmund S (2007a) Investigation of dimension stones in Thailand: an approach to a methodology for the assessment of stone deposits. In: Siegesmund S, Ehling A (eds) Rohstoff Naturstein. Z dt Ges Geowiss 158(3):375–416

Hoffmann A, Siegesmund S (2007b) The dimension stone potential of Thailand—overview and granite site investigation. In: Prikryl R, Smith BJ (eds) Building stone decay: from diagnosis to conservation. Geological Society of London, Special Publications 271, pp 43–54

ISRM (1978) Suggested methods for the quantitative description of discontinuities in rock masses. International Society for Rock Mechanics Commission on Standards of Laboratory and Field Tests. Int J Rock Mech Min Sci Geodyn Abstracts, 15/6:319–368

Koch-Moeck M, Germann K (2007) Geowissenschaftliche Optimierung der untertägigen Gewinnung von Marmor. In: Siegesmund S, Ehling A (eds) Rohstoff Naturstein. Z dt Ges Geowiss 158(3): 491–500

Lu P, Latham JP (1999) Developments in the assessment of in situ block size distributions of rock masses. Rock Mech Rock Eng 32(1):29–49

Montani C (2003) Stone 2002—World marketing handbook. Faenza, GruppoEditorial Faenza Editrice

Mosch S (2009) Optimierung der Exploration, Gewinnung und Materialcharakterisierung von Naturwerksteinen. Dissertation Univers. Göttingen, p 276

Mosch S, Nikolayev D, Ewiak O, Siegesmund S (2009) Optimierung der Werksteingewinnung mit 3D-BlockExpert. Steinbruch Sandgrube 5:8–11

Nikolayew D, Siegesmund S, Mosch S, Hoffmann A (2007) Modell-based prediction of unfractured rock masses. Z dt Ges Geowiss 158(3):483–490

Palmström A (1995) RMi—a rock mass characterisation system for rock engineering purposes. Ph.D thesis of the University of Oslo, Norway

Priest SD (1993) Discontinuity analysis for rock engineering. Chapman and Hall, London, p 473

Primavori P (1999) Planet stone. Giorgio 7th Edition S.A.S., Verona, p 326

Prissang R, Hella P, Lehtimäki T, Saksa P, Nummela J, Vuento A (2006) Lokalisierung ungestörter Blöcke in größeren Gesteinsmassen. In: Dominik W, Roehling H-G, Stackebrandt W, Schroeder J-H, Uhlmann O (Hrsg) GeoBerlin 2006. 3D-Geologie—eine neue Chance für die Nutzung und den Schutz des Untergrundes, Berlin, 2–4. Oktober 2006. Schriftenreihe der Deutschen Gesellschaft für Geowissenschaften 50, Abstract p 60

Prissang R, Hella P, Lehtimäki T, Saksa P, Nummela J, Vuento A (2007) Lokalisierung ungestörter Blöcke in größeren Gesteinsmassen. Z dt Ges Geowiss 158(3):471–482

Siegesmund S, Nikolayev D, Mosch S, Hoffmann A (2007) 3D-BlockExpert. Naturstein 5:102–107

Singewald C (1992) Naturstein—Exploration und Gewinnung. Rudolf Mueller, Bad Bentheim, p 260

Smith MR (ed) (1999) Stone: building stone, rock fill and armour stone in construction. Geological Society of London, Engineering Geology, Special Publications, vol 16

Sousa LMA (2010) Evaluation of joints in granitic outcrops for dimension stone exploitation. Q J Eng Geol Hdrogeol (in press)

United Nations (1976) The development potential of dimension stone. Department of Economic and Social Affairs, ST/ESA/34, p 95, New York

Weber J, Lepper J (2002) Depositional environment and diagenesis as controlling factors for petro-physical properties and weathering resistance of siliciclastic dimension stones: integrative case study on the 'Wesersandstein' (northern Germany, Middle Bundsandstein). In: Siegesmund S, Weiss T, Vollbrecht A (eds) Natural stone, Weathering phenomena, Conservation strategies and Case studies. Geological Society of London, Special Publications 205, pp 103–114

Weber J, Dehnhart J, Lepper J (2001) Trennflachenanalyse zur Vorratsermittlung von Naturwerkstein Lagerstatten. Z Angew Geol 47(2):74–78