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МИНЕРАЛОГИЧЕСКИЙ И МИКРОСТРУКТУРНЫЙ АНАЛИЗ АНИЗОТРОПНЫХ ПОРОД: ГНЕЙС ИЗ ЭРЦГЕБИРГЕ КАК ПРИМЕР ИССЛЕДОВАНИЯ

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Аннотация: Анизотропия является одной из наиболее важных характеристик, которые необходимо учитывать при оценке измельчения. Оценка физических и минералогических свойств обеспечивает параметры для оптимизации процесса измельчения с использованием естественного поведения сырья при дроблении, которое в основном связано с текстурой и структурой горных пород. Минералогические и петрографические характеристики играют важную роль и должны быть максимально точными, чтобы предсказать реакцию горных пород на механическое воздействие. В данной статье представлены первые результаты определения характеристик с использованием интеграции методов оптической микроскопии с численным описанием с помощью количественного микроструктурного анализа (QMA), трехмерной характеристики с помощью микрокомпьютерной томографии (μCT) и экспериментов по дилатометрии. Интеграция этих методов в первую очередь направлена на то, чтобы увидеть применимость QMA к анизотропным материалам и получить текстурные и структурные параметры. Анализы проводились на гнейсах из шахтерского района Саксонии, Эрцгебирге (Рудные горы), Германия.

Ключевые слова: количественный микроструктурный анализ, гнейс Фрейберга, анизотропная характеристика.

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Mineralogical and Microstructural Analysis in Anisotropic Rocks: Gneiss from Erzgebirge as a case of study

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Abstract: Anisotropy is one of the most important features that must be considered in the evaluation for comminution. The evaluation of physical and mineralogical properties provides parameters to optimize the size reduction process using the natural crushing behaviour of raw materials, which is mainly linked to the texture and structure of the rocks. Mineralogical and petrographic characterisation plays an important role and must be as accurate as possible to predict the response of rocks to mechanical stress. This article presents the first results of characterisation using the integration of optical microscopy techniques with numerical description by Quantitative Microstructural Analysis (QMA), three-dimensional characterisation by microcomputed tomography (μCT) and dilatometry experiments. The integration of these techniques primarily aims at seeing the applicability of QMA to anisotropic materials and obtaining textural and structural parameters. The analyses were conducted on gneisses from the Saxony´s mining district, Erzgebirge (Ore Mountains), Germany.

Key words: quantitative microstructural analysis, Freiberg gneiss, anisotropic characterisation.

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1. Introduction

Anisotropy is an intrinsic characteristic of intact foliated rocks, such as gneisses, and influences the behaviour of mechanical properties, like strength and deformation [1, 2]. The anisotropic behaviour is the result of the rock's mineral composition and geological processes [3]. This relationship has been studied for decades from different perspectives, showing the importance of micro-textural parameters on physical and mechanical properties of rocks [4, 5]. Micro-textural parameters refer to the distribution of minerals, their orientation, shape, the internal textures, among others [6], which reflect the processes of rock formation. In the case of metamorphic rocks such as gneiss, these generally show a high degree of anisotropy, which depends on the degree of orientation of their constituents. A typical example are the layered silicates, which have been orientated by a process of sedimentation or under a specific stress regime during metamorphic processes [3].

Raw materials processing is an activity that usually operates with high energy consumption. One of the most important stages in this context is the liberation of valuable minerals from the ore, which requires the disintegration of rocks into small particles. This process is known as comminution and accounts for more than 50% of the energy consumption of the entire process [7, 8]. On average, it is estimated at 36% of the total energy utilised by the mines [9, 10]. New studies tend to refer to this process as one of the important points to improve, covering both the optimisation in the use of machinery [11] and the exploitation of the mechanical and mineralogical characteristics of the material [12–14]. Selective comminution is a promising process for reduce the specific energy consumption, however it must apply correctly to separate the portions of material with no or low mineral or metal concentrate [12].

When evaluating a rock, e.g., for comminution processes, the properties of minerals should be well understood [15, 16]. A deeper knowledge about the microstructures is an important aspect for understanding crack propagation and especially the influence of pre-existing imperfections in the rock [17, 18]. Even though the currently common mineralogical-petrographic characterisation of rocks allows the description of the microstructure, a quantitative analysis is needed for the assessment of rocks in terms of crushability and product particle shape [15, 19]. The influence of rock and ore properties on the processing characteristics has led to several efforts to introduce new technologies into the analysis. In recent times, there has been a growing interest in the question of how to deal with the evaluation of mineralogical characteristics and how to combine different analytical techniques for a proper interpretation of the material.

A mining area that has presented particular in the processing is located on one of the major mining districts in Saxony, the Erzgebirge (Ore Mountains) in Germany. Erzgebirge is mainly composed of gneisses that show complex nature. For example, the measured coefficient expansion of gneiss generally behaves transversely isotropic, where the anisotropic direction of which is perpendicular to the foliation plane [20]. Schreiber [21], using uniaxial compression tests, determined that higher compressive strength is measured parallel to the foliation rather than perpendicular.

To investigate this compression test response anomaly in gneiss, this study firstly shows an analysis of gneisses from the Freiberg area by QMA, prepared according to their foliation direction. This analysis was performed at the facilities of the Institute of Processing Machines and Recycling Systems Technology (IART) at the TU Bergakademie Freiberg. The statistical evaluation of three orthogonal thin sections allows a quantitative assessment of the mineral phase composition, the shape, and orientation of mineral grains in each rock, which can be used to approximate its mechanical properties. This research aims to assess the applicability of QMA for gneisses and to incorporate other techniques, such as dilatometry and micro-computed tomography, that can provide textural and structural information and integrate it with data through microstructural analysis.

2. Materials and methods

1.1. Rock samples

The material under study consists of Freiberg gneiss samples derived from a drill core (Fig. 1a) from the Reiche Zeche mine, which belong to the TU Bergakademie Freiberg, and hand sampling from the same location (Fig. 1b), as well as from the Dörfel area, located about 60 km to the SW of Freiberg (Fig. 2). Freiberg gneiss is a grey augen gneiss formed by high metamorphism of Early Cambrian granodiorite [22] and its main mineral phases are plagioclase,

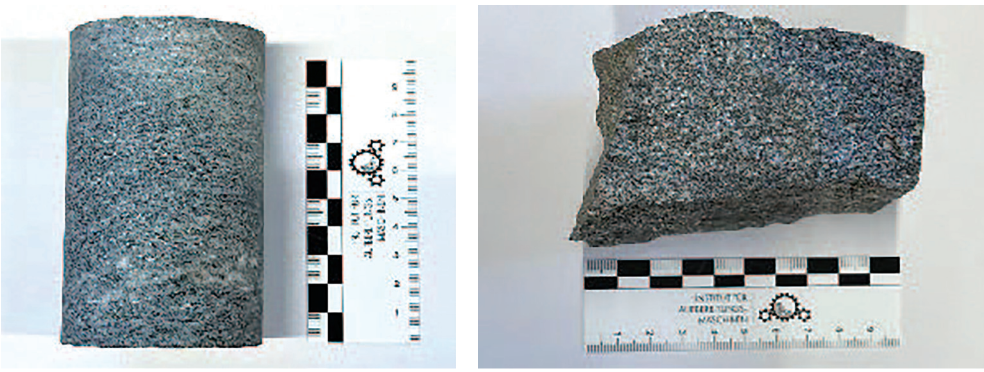


Fig. 1. Gneiss samples (a) core specimen orientated, (b) hand sample from the same area

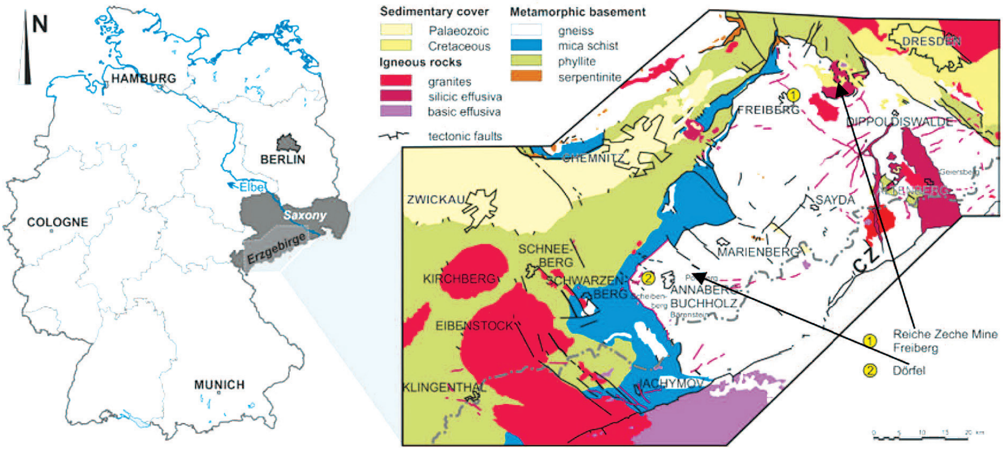


Fig. 2. Geological map of Saxony with sampling locations (1 & 2). The gneiss area is highlighted in white [13].

quartz, biotite and K-feldspar. The material from Reiche Zeche area has served as international reference material for mineralogy, petrography, and geochemistry, which provides a good base for accumulating reliable information on their mechanical behaviour [13].

The volumetric portion for each phase was determined by QMA and X-Ray powder diffraction analysis (XRD) with Rietveld refinement, in which the distribution of the main phases was obtained (Quartz 23%, mica 20% and grouped Feldspar, considering Plagioclase and K-Feldspar, 57%)

1.2. Methods

Representative gneiss samples were collected at Reiche Zeche and prepared in the cubic form to obtain three thin sections, with an orientation orthogonal to each other. The samples were examined under a conventional optical microscope with transmitted and reflected light to describe and determine qualitative mineralogical data (mineral phases, alterations) and geometric information of the samples (texture, structure). Microscopic analysis was conducted using the polarised light microscope Axio imager, A1m (Zeiss), equipped with a high-resolution digital camera Zeiss AxioCam. This conventional analysis method provides a non-destructive way to identify phases within the textural frameworks, with relatively high spatial resolution. From the same cubic samples, nine pieces (25x5x5 mm) were obtained with different orientations (horizontal, vertical and 45° to the foliation) for thermal treatment using a dilatometer. The pieces were investigated also using Scanning Electron Microscope (SEM) before thermal exposure, to visualise possible changes after heat treatment. The SEM equipment model JSM-7001F (JEOL) has a wolfram filament as the field emission cathode. Gneiss' data from Dörfel with similar dimensions (20x5x5 mm) and thermal treatment were compared with the results. Six small cylinders (18x30 mm) with the same orientation were also prepared from the cubes for microcomputed tomography descriptions. Once dilatometric data as well as textural and structural parameters were obtained, the parameters were compared to evaluate the QMA technique. The combination of these methods provides data on rock properties and allows assessment of the properties of the raw rock. It was important to consider non-destructive methods, as they are ideal for comparing materials before and after deformation treatment.

1.2.1. QMA — Quantitative Microstructural Analysis

The QMA is a method of mathematical-statistical 3D description of ore and rock structures [15]. Since mineral grains have a complex three-dimensional shape and their physical properties are distributed anisotropically, according to the QMA approach developed at the IART, three thin sections orthogonal to each other are necessary and were therefore prepared from the gneiss. These samples were evaluated with the help of a polarisation microscope, assessed by means of various stereological methods (Fig. 3), and classified in a library of thin sections. A mathematical model was used to characterise the rock quantitatively, based on the calculation of relevant structural and textural characteristic data.

The magnification and adequate filters for optical microscopy were determined

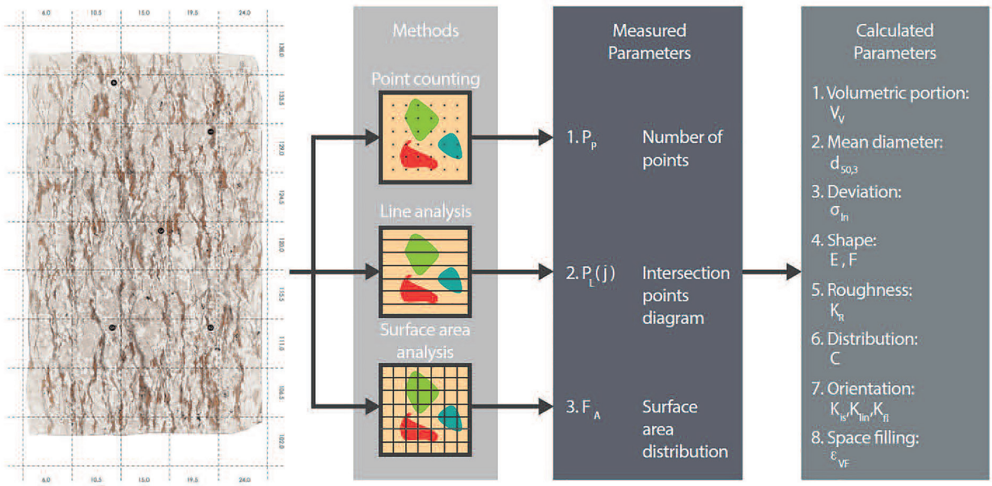


Fig. 3. QMA — point, linear and areal analysis methods for thin sections. Microphotography of a gneiss thin section specimen from Freiberg (left)

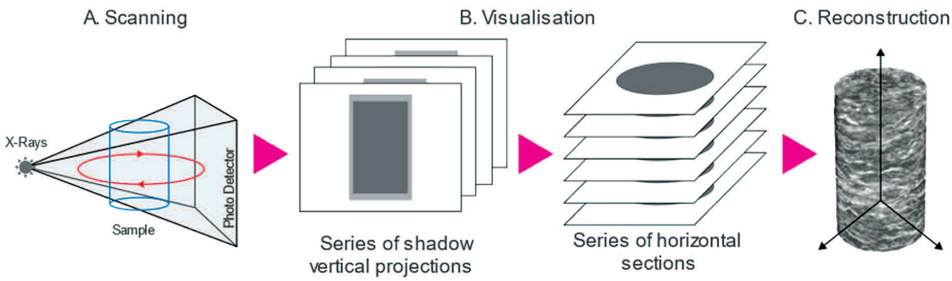


Fig. 4. Basic principles of CT. (a) Scanning of the sample in X-ray beam; (b) Mathematical transformation of the shadow vertical projections into a series of horizontal sections of the object; (c) Creation of three-dimensional images of the sample for Freiberg gneiss. Figures modified from Popov, 2020 [6]

in relation to the size of the grains in the sample, where the section area analysed must contain as many grains as possible and should be chosen at randomly (Fig. 3) to ensure representativeness of the results. The grain quantity per image and the total number of single images to be analysed must be manageable by the operator [23].

For the interpretation of the effects of gneiss and its anisotropic nature, in this study, an analysis is made mainly of the parameters obtained by QMA. Within the parameters, a more detailed evaluation of grain shape, roughness and degree of anisotropy is made and compared with theoretical results for isotropic and anisotropic values. The grain shape is associated and determined by roughness and grain shape of a microbodies, according to the elongation and flatness of the grains.

1.2.2. X-Ray micro-Computed Tomography (μCT)

X-ray μCT is a non-destructive imaging technique and evolved as an effective supplement in complex studies of petrophysical properties of rocks [6]. The X-ray μCT instrument acquires one or two-dimensional radiographs from different positions, from which a three-dimensional image is computationally reconstructed (Fig. 4). The method consists in weakening the power of the X-ray beam when passing through a certain volume of the material. Using appropriate filters behind the sample (Al or brass filters), the result of the scan can be fixed by the shadow projections. The value is expressed in 256 grey colour shades. The μCT was carried out at the Institute of Rock Mechanics at Mining University, Saint Petersburg (Russia) using a BRUKER CT-scanner and certified programmes Skyscan1173 μCT, NRecon, DataViewer, CTVox, CTAn, and CTVol. The setup considered a voltage of 130 kV and 61 mA current rate. Additionally, a 0.25 mm brass filter and 0.200-degree rotation step were used with a maximum resolution of 32 microns. In this first instance, it was validated the reconstruction of images with the resolution mentioned, for the identification of pores, mineral phases, and structure.

1.2.3. Dilatometry analysis

Dilatometry is a technique in which the dimension of a substance under load is measured as a function of temperature, while the substance is subjected to a controlled temperature program, by using dilatometer devices. Dilatometric tests can measure the variation in the length of the specimen after heating or/and cooling-heating cycles program. Considering the heterogeneity factor of a rock, the thermal expansion of minerals (also heterogenous) generates the formation of microcracks within and between the mineral grains [24, 25]. When a substance is heated, its constituent atoms stay with the greater average separation ratio [26]. In the framework of this research, the dilatometer used is a Netzsch DIL 402c dilatometer, Netzsch Version 4.8.3, Type S thermocouple, and a High RG2 DIL 402c furnace. The equipment is located at the Institute of Mineralogy of the Technical University of Freiberg. The measurement mode was a standard expansion with an Al_2O_3 sample holder with a diameter of 30 mm. The test conditions were atmosphere: Argon; 50 ml/min and the initial temperature of 25°C. In the first instance, dynamic heating of 1000°C; 5K/min and dynamic cooling of 500°C; 5K/min was achieved. This process was repeated three times for each orientation described above. It was sought to find if there is a relationship between orientation and the type of fracture observed in the samples. In the case of the data for the Dörfel specimens, the tests were measured at the Institute for Ceramics, Glass, and

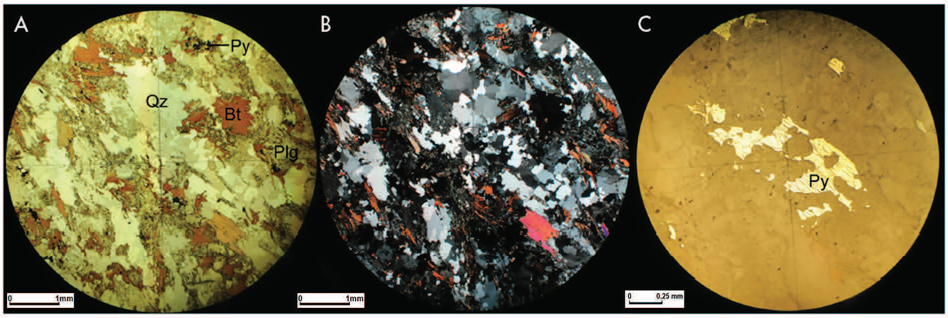


Fig. 5. Gneiss thin section microphotographs. Main minerals: quartz (Qz), biotite (Bt), plagioclase (Plg), pyrite (Py). Preferential orientation of minerals on microphotographs 45°. (a) TL (Transmitted light), Ppol (Plane-polarised light), (b) TL, Xpol (Cross-polarised light), (c) RL (Reflected light)

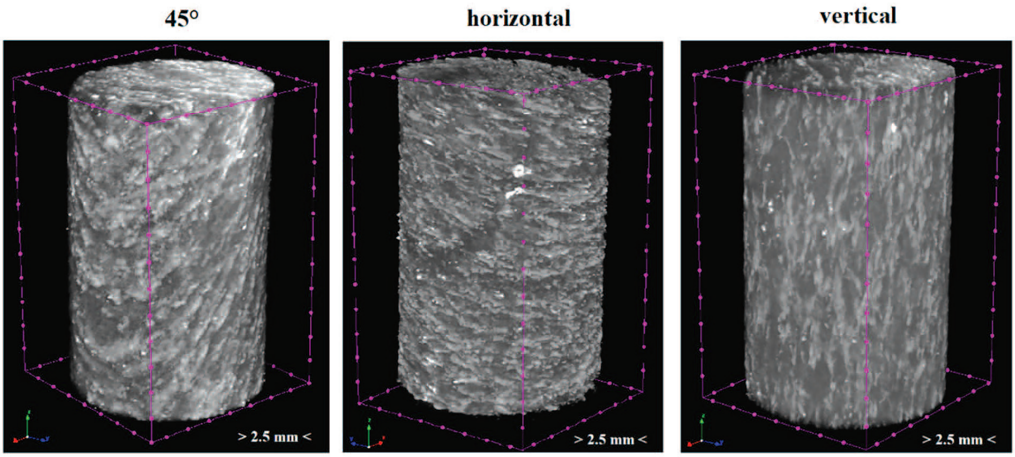


Fig. 6. Reconstruction of three-dimensional images of the Freiberg gneiss according to the main foliation

Composite Materials (TUBAF), with a heating and cooling one-cycle, up to 900°C. Same condition were also applied for gneiss from Freiberg. Based on this analysis, the coefficient of linear thermal expansion (CLTE) which describes the change in length of a material as a function of temperature is calculated.

2. Results and discussion

2.1. Mineral phase distribution under a conventional microscope

The gneiss described under microscope (Fig. 5a and 5b) shows the spatial relationship between the different mineral phases and their foliated crystals (lepidoblastic texture). The quartz crystals

Table 1
Morphometric indicators of the Freiberg gneiss obtained by X-Ray µCT

#Samples	Isolated Porosity Volume [mm³]	Isolated Porosity Area [mm²]	Isolated Porosity [%]	Effective Porosity Volume [mm³]	effective Porosity [%]	Total volume of pore space [mm³]	Total Porosity [%]
45°	0.494	136.166	0.056	0.017	0.002	0.51055	0.058
horizontal	4.799	996.139	0.521	0.166	0.018	4.96514	0.539
Vertical	43.992	7411.523	1.785	2.495	0.101	46.48627	1.884

are very irregular and are observed in contact with each other as well as with plagioclase. Muscovite is also locally represented in heaps. Crystals of plagioclase are difficult to distinguish in grains widely altered to sericite (medium grade) and clays, but most of the grains show typical twin's structure.

Biotite altered to chlorite (low birefringence colours). Feldspar altered to clays and sericite. Pyrite crystals with a maximum size of 1 mm (Fig. 5c) are also observed in a disseminated occurrence, filling spaces. Locally pre-cracks are found, mainly associated with the boundaries between quartz and feldspar.

2.2. Porosity factor and μCT reconstruction

Using CTvox and CTan software, the samples were examined in terms of porosity (Table 1). The porosity factor is directly linked to the behaviour of the material and often determines the strength characteristics of the rock [27]. When analysing the pore space characteristics of the samples according to orientation, it was shown that the samples have low porosity in all cases, with local porosity for samples in vertical orientation and parallel to the foliation according to their maximum length. It is then possible to categorise the Freiberg gneiss as having a high strength of the rock itself. The quartz and feldspar grains tend to accumulate, forming clusters, which cannot be observed under μCT (Fig. 6).

2.3. Parameters obtained by QMA and relation to experimental studies

QMA is suitable for the quantitative description of the Freiberg gneiss, because this method allows to obtain the anisotropic texture of this metamorphic rock. For the rock-mechanical evaluation, minerals with similar mechanical properties, such as alkali feldspar and plagioclase, can be grouped together. Starting from the identification of mineral phases and the respective grain relationship, textural and structural parameters are presented (Table 2).

2.1.1. Grain shape, roughness, and grain size

The overall grain shape of all minerals of Freiberg gneiss is mainly needle-platy ($a >> b > c$), with elongation and flatness values (E = 2.329; F = 1.126) (Fig. 7a). The grain shape of the mica is described as needle-shaped ($a >>> b > c$). This is confirmed the values of elongation and flatness (E = 3.037; F = 1.161). For quartz and feldspar, the values of elongation and flatness are more similar (Table 2.). Relating the theoretical parameters, the elongation and flatness values tend to be similar for isotropic material (Fig. 7b) in contracts for the results obtained after QMA for gneiss from Freiberg (Fig. 7c). The K_R roughness of the mica minerals is approximately 35%, quartz 4%, and Feldspar 1%. These values are expected for the theoretical ratios for gneiss.

The mean grain size of all minerals is similar for each main phases in gneiss from Freiberg. The grains of quartz show a mean grain size of 200 μm, the feldspar's grains 155μm and the grains of mica 152μm. The overall mean grain size of the rock is 228 μm (Table 2). The diameter distribution of the mica shows a scatter parameter of 0.478, relatively lower than for quartz and feldspar (0.500 and 0.518 respectively).

2.1.2. *Degree of clustering and isotropic orientation*

The linear analysis provides the opportunity for determining the degree of clustering of grains. This parameter is important to predict the size fractionation, crucial to achieve pre-defined enrichment in selective comminution. The mica shows a 9% cluster formation, which means that 9% of mica lies next to another mica grain surface. In the case of quartz and feldspar phases, the degree of clustering reaches 25 and 7%, respectively (Table 2). Results

Table 2
Rock characteristics as established by QMA under the optical microscope

Raw Material			Type: Freiberg gneiss Location: Reiche Zeche, Freiberg, Germany			Phase Related features			Raw Material features
Mode			**Properties**	**Kind**	**Unit**	**Quartz**	**Feldspar**	**Mica**	**Σ Microbodies**
		Content	Volumetric Portion	ε_V	%	23	57	20	100
Fabric	**Texture**	**Size**	Mean diameter	$d_{50,3}$	mm	0.200	0.155	0.152	0.228
			Deviation	σ_{ln}	-	0.500	0.518	0.478	0.580
		Grain surface	Specific surface	S_v	mm^2/mm^3	21.620	9.070	15.360	12.260
		Shape	Elongation	E	-	1.605	1.762	3.037	2.329
			Flatness	F	-	1.102	1.232	1.161	1.126
		Roughness	Roughness degree	K_R	%	4	1	21	6
	Structure	**Orientation**	Degree of areal orientation	K_{fl}	%	5	11	9	7
			Degree of isotropic orientation	K_{is}	%	64	56	35	46
		Distribution	Degree of clustering	C	%	25	7	9	15
		Space filling	Space filling degree	εVF	%	-	100	-	100

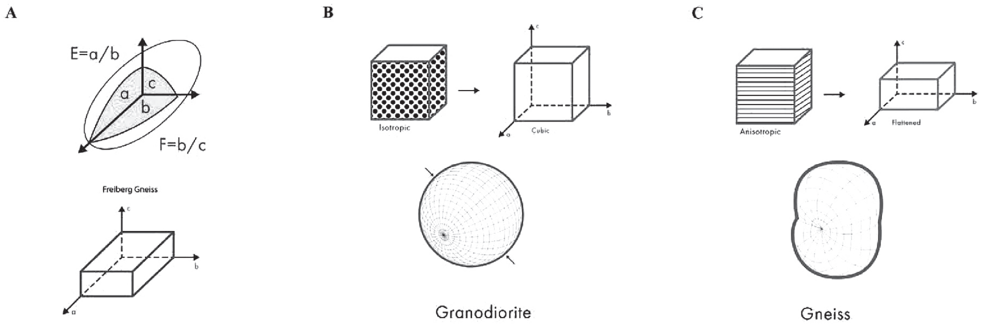


Fig. 7. (a) Two-plane projection for ratios of elongation (E = a / b) and flatness (F = b / c) results for gneiss from Freiberg; (b) Theoretical projection diagrams for isotropic rock (granodiorite); (c) Theoretical projection diagrams for anisotropic rocks (gneiss)

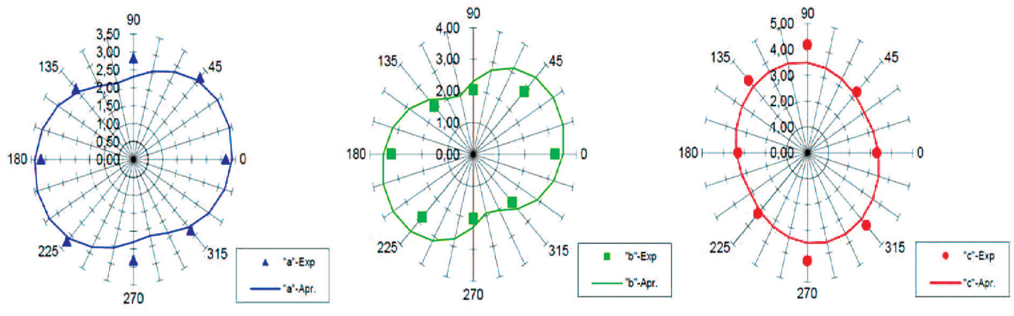


Fig. 8. 2D intersection roses for Freiberg gneiss

of linear analysis can be presented in the form of two-dimensional intersection roses (Fig. 8), which show the number of intersections along the lines at varied intersection angles with the thin section. Based on the three intersection roses orthogonal to each other, a spatial rose of intersections and their orientation in space can be calculated (*a*, *b* and *c*).

When observing the grains under microscope, quartz, K-felspar and plagioclase grains are observed as cluster areas locally. Those textures influence on the percentage of the degree of clustering. Those clusters cannot be observed with μCT (Fig 6).

A spatial intersection rose of an orientated microstructure is the superposition of the roses of intersections of ideal boundary surface systems. From the parameters of the spatial rose of intersections the orientation degrees (K_{is}, K_{lin} and K_{fl}) of the spatial arrangement (percentages of linear- and areal-oriented as well as non-orientated boundary surfaces) can be derived [15].

The isotropic orientation degree K_{is} is about 46%. Based on tests, it is possible to ascertain, that rocks with an isotropic K_{is} orientation in the range of 40 and 75% (Fig. 9) provide indications that the generation of cubic products is possible only by means of greater mechanical complexity (higher number of comminution chambers) and with a modified mode of operation of the processing machine or system (the optimum feed rate for filling of comminution machines). This result is expected due to the anisotropic behaviour of the Freiberg gneiss.

The degree of clustering can be calculated with the linear counting method in QMA. In the case of CT analysis, it is challenging to define the boundaries between quartz and feldspar, since the CT scopes are not sufficient to measure separate grains with the similar density (Quartz-Feldspar). Therefore, the degree of clustering cannot be easily determined as mentioned previously.

3.1.4 Integration of textural approach, fracturing and thermal expansion

One of the physical attributes that are important to know when a material is to be processed is to evaluate how the material responds to changing ambient conditions. Orientated pieces of gneiss were exposed to temperature cycles to determine the thermal coefficient. The heating-cooling cycles, as mentioned above, reached temperatures up to 1000°C and were cooled down to 500°C before the cycles were completed. The SEM images can also be used to estimate the type of fracture after the cycles. Interfacial or intergranular (between grain boundaries) and preferential breakage (intragranular) are observed in all samples (Fig. 10b, 10c).

The graph of the coefficient of thermal expansion (Fig. 11) shows tests for Dörfel gneiss, exposed to temperatures up to 800°C. When looking at the blue curve (orientation perpendicular to foliation), the coefficient is relatively higher than the curves with material samples with parallel orientation (orange and green).

Targeted assays for Freiberg gneiss were treated at the same conditions. Single cycle up to 900°C and cooled down to 200°C to check if there is any difference with the temperature test response between gneiss and the orientation and the isotropic degree (Fig. 12a) (a granodiorite with similar composition was exposed to the same condition).

Analysing the data obtained from the measurements for Freiberg gneiss and granodiorite, quartz transformation occurs at temperatures close to 560°C for each case (Fig. 12b). A change in the curve is seen in the case of granodiorite, possibly attributed to the fact that when analysing under the optical microscope a greater

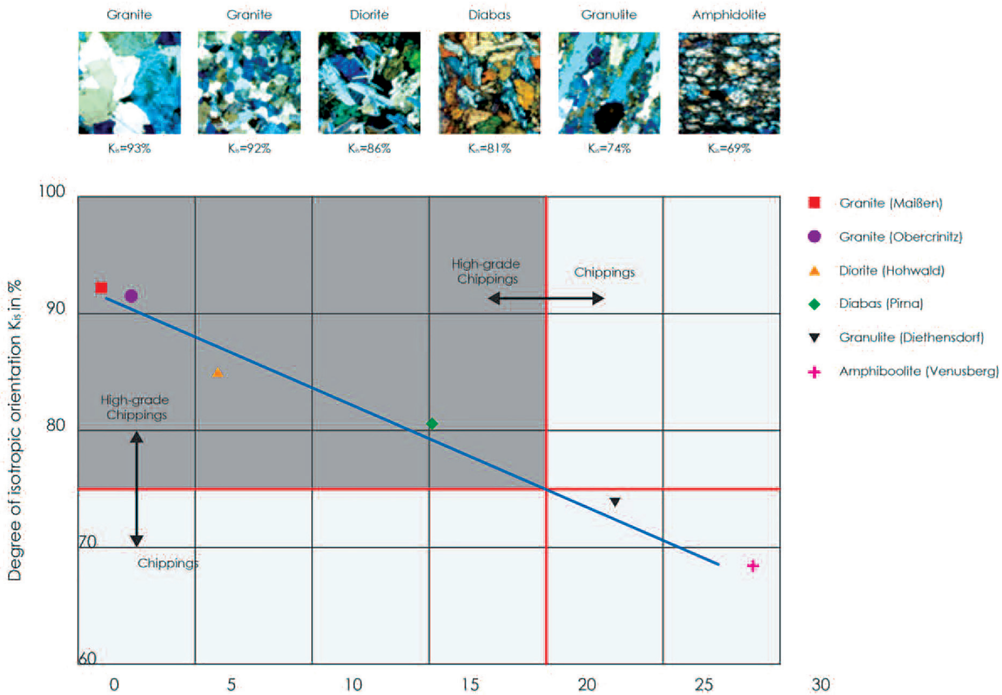


Fig. 9. Correlation between isotropic Kis orientation and non-cubic particle content FK5/8 (comminution in a rotary centrifugal mill, feed material 16/32 mm), modified from Popov, 2014 [15]

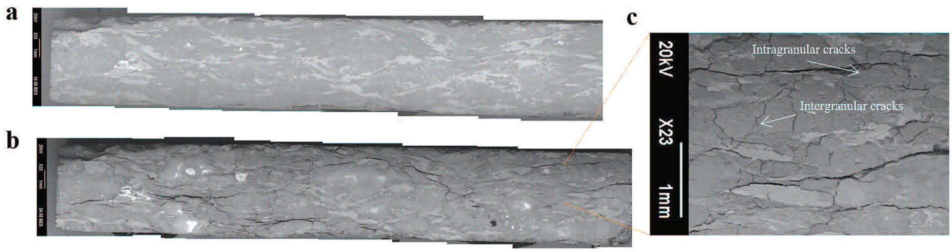


Fig. 10. (a) SEM Microphotographs, backscattered electron mode (BSE), of Freiberg gneiss pieces orientated without temperature treatment; (b) microphotographs under SEM; of Freiberg gneiss pieces orientated after temperature treatment; (c) zoom in on cracks after temperature treatment

amount of plagioclase altered to sericite and clays are observed, which could be generating this variation.

The dilatometric curve presents a non-linear volumetric up to the phase transformation temperature in all cases. After reaching the peak, the volumetric expansion of samples in perpendicular orientation to the foliation is equal to samples orientated in 45°C and higher than the parallel orientation.

This «anomaly» in behaviour with respect to the foliation, was also reported in tests without thermal treatment [21], where the values for the uniaxial compressive strength were 163.3MPa parallel to foliation and 121.9MPa perpendicular to foliation. The results suggest that regardless of whether induced thermal treatment or compression tests are performed, there is a dependence of fracture propagation on the orientation and textural dependence.

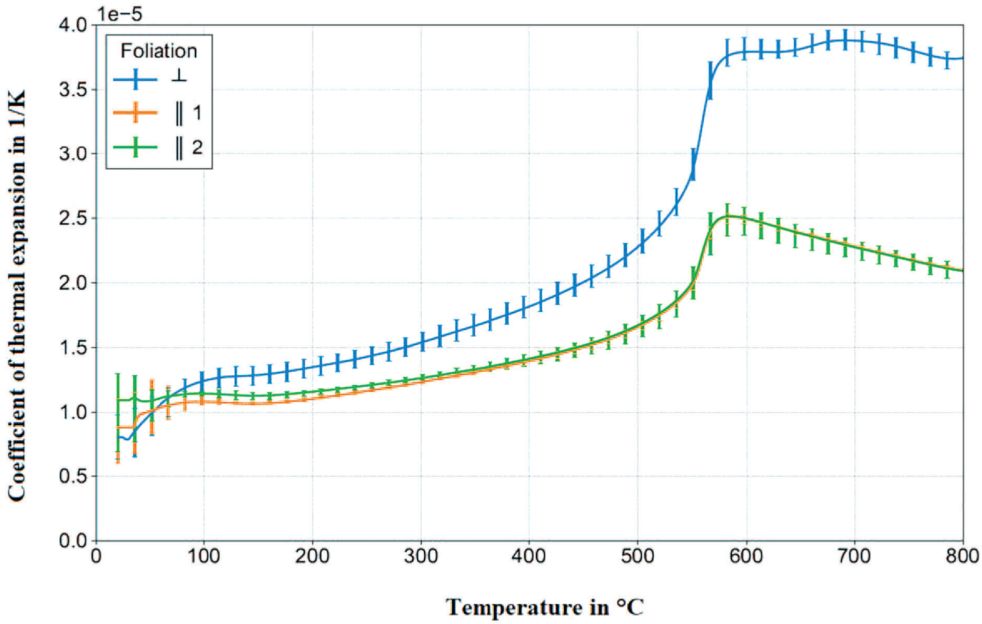


Fig. 11. Thermal expansion coefficient calculated for Dörfel gneiss, perpendicular (blue) and parallel to foliation (green/orange). Averaged measurements in each direction are shown with error marks for 3 samples for each orientation [20]

These results combined with microscopic textural studies, can be explained by the fact that mica in the Freiberg gneiss displays a planar anisotropic orientation in the x-y plane (Fig. 10a). A predominance of fracturing along the x-y foliation plane is observed. Determination of the predominant fracture type requires further analysis to determine if there is a dependence on the sample.

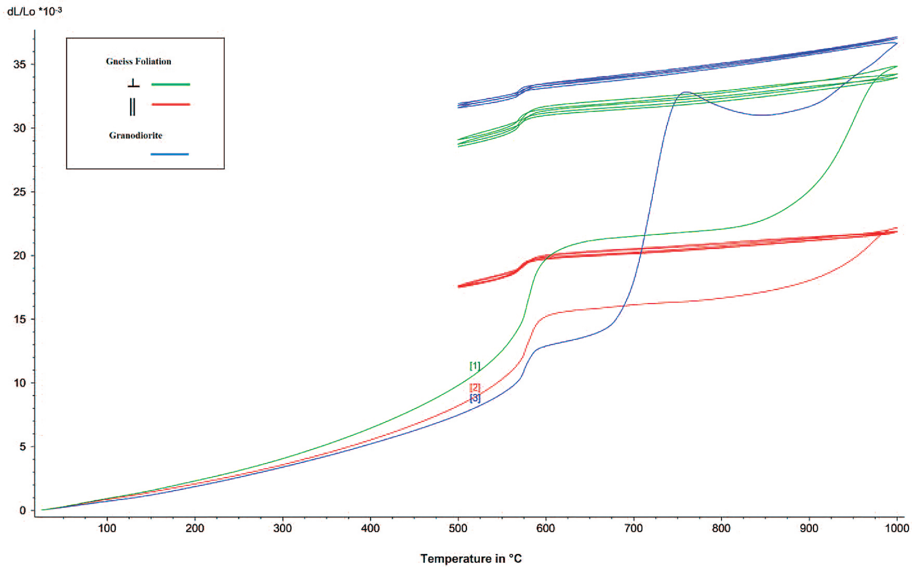
3. Conclusion

The Freiberg gneiss was used to evaluate the applicability of quantitative microstructural analysis (QMA) in anisotropic material and how microstructural parameters can be evaluated and correlated with other analytical techniques, leading to the following conclusions:

– The QMA technique is useful for the evaluation of gneiss from Erzgebirge. QMA provides accurate textural and structural characterisation. The overall grain shape of all gneiss minerals from Freiberg showed a needle-platy elongation, which was also observed under a polarised microscope.

– The orientation of microstructural constituents was determined by the degree of orientation, which is an important criterion for the assessment of the product particle shape. The rock characteristic values estimate the rock regarding crushability and product particle shape. Prediction is achieved by integrating structural and textural parameters such as orientation, roughness, shape, and size.

– The isotropic orientation of K_{is} indicates that the generation of cubic products in gneiss from Erzgebirge is only possible with a higher number of comminution stages. The value obtained by QMA analysis for the isotropic orientation degree K_{is} is about 46%.



Parallel Freiberg Gneiss

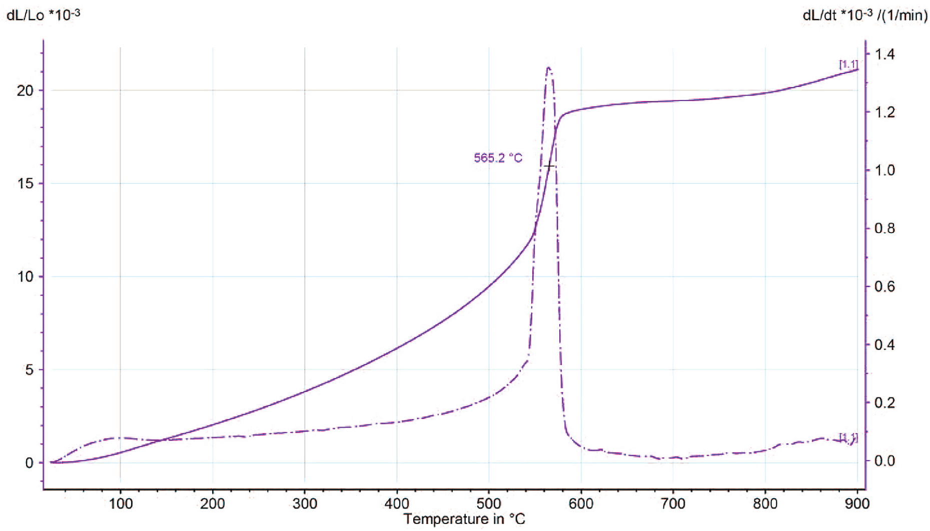


Fig. 12. (a) Relative length change (dL/Lo) vs Temperature of a gneiss (parallel and perpendicular cases) and granodiorite that show the cycles of heating-cooling over the time under dilatometry analyses. (b) Diagram of the coefficient of thermal expansion with respect to temperature for parallel gneiss 20.0°C/5.0(K/min)/900°C, showing the expansion curve, and quartz transition phase at 565.2°C

It is important to keep in mind that these values of rock characteristics were first determined independently, without considering specific applications or processing. Therefore, a great advantage of this method is that the values of quantitative characteristics remain constant, and only their specific application changes.

– The investigative power of microcomputer tomography (µCT) gives us an idea of the distribution of mineral phases and porosity. However, it does not allow us to evaluate grain boundaries between feldspar and quartz.

– Thermal analysis using dilatometry confirms that the coefficient of thermal expansion is higher in the direction orthogonal to the foliation than in the parallel direction. Future studies will focus on complementing the textural influence of induced deformation tests.

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