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Acoustic Emission Characteristics and Failure of Uniaxially Stressed Granitic Rocks: the Effect of Rock Fabric

By

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Summary

Laboratory experiments on rock samples were carried out to understand the relationship between the acoustic emission (AE) parameters and rock fabric. AE activity was recorded during the uniaxial compression with constant stress rate of several granitic rocks showing variable microfabric (e.g. grain size, shape and crystallographic preferred orientation) and macrofabric (e.g. magmatic isorientation, metamorphic banding). A broad band multichannel recording system with a high dynamic recording range enabled individual acoustic emission events to be analysed in a wide frequency and energy range. The microfabric of the rocks was studied by quantitative petrographic analysis of thin sections allowing precise description of mode, grain size and shape. It has been proved that the energy-frequency distribution of AE events strongly reflects the fabric of the samples. The characteristic energy value of AE events reflects the most frequently occurring grain dimensions. The AE parameters like acoustic rate or cumulative energy are highly sensitive to fabric arrangement in rocks with pronounced fabric (e.g. foliation, lineation etc.).

Keywords: Acoustic emission, energy-frequency distribution, rock fabric, grain size distribution, fracture pattern.

1. Introduction

The energy-frequency distribution of the acoustic emission (AE) radiated from loaded rock structures characterises the process of elastic energy release from seismoacoustic brittle fracture regions. This distribution indicates the relation between the occurrence of weak and strong events. The results of laboratory experiments are important not only for interpreting the data from seismic active regions (Oda et al., 1989; Lockner, 1993; Rudajev et al., 1994a) but also for studying the rock fabric as will be discussed later. From the seismological point of view the distribution is of fundamental importance in classifying the seismicity of different regions, and also for seismic hazard assessment. It has been extrapolated empirically using a negative exponential relation (Epstein and Lomnitz, 1966):

$$\log(N(E)) = a - b \cdot \log(E), \tag{1}$$

where a and b are parameters of the distribution, which may vary with the time or place of observation, and $N(E)$ is the number of seismic events with energy E. The loading process (prevailing components of the stress tensor and time variations of the stress rate), the seismic zone structure and its physical properties are the main factors controlling these changes. Further analysis of the energy-frequency distribution of AE events radiated from uniaxially loaded samples proved their bilogarithmic distribution (Rudajev et al., 1998):

$$N(\ln E) = \frac{1}{\mathrm{K}} \cdot e^{\frac{-(\ln E - \mathrm{k})^2}{2d^2}}, \tag{2}$$

where K, k are the constants of the distribution, and d is the dispersion.

Since the first applications of AE monitoring were motivated by a desire to predict mine failures or slope stability (Goodman and Blake, 1965; Wisecarver et al., 1969), the later development lead to the frequent use of AE as a passive method sensitive to the growth of defects during the laboratory deformational tests of different rocks like sandstones (Deflandre et al., 1995; Zang et al., 1996), granitoids (Thill, 1972; Montoto et al., 1981; Rao and Ramana, 1992; Shah and Labuz, 1995), andezites (Rao and Kusunose, 1995) or tuffs (Shi et al., 1995). Further, the application of AE as an indicator of prior stress conditions was based on the so called Kaiser effect (compare Holcomb, 1993). Amplitude of AE was related to geometric properties like crack size (Cox and Meredith, 1993).

These studies demonstrated that AE monitoring is sensitive to different stages of rock disintegration during laboratory deformation regardless the type of rock and intensity of its fabric. Our study, on contrary, aims to point out the influence of some fabric parameters of natural rocks on AE characteristics obtained during laboratory experiments.

2. Theory

The acoustic waves radiated at ultrasonic frequency are characterised by the amplitude x of displacement, frequency f and wavelength λ. All these parameters are connected with the properties of the source and media. The following relations apply:

$$v_{\mathrm{P,S}} = \lambda_{\mathrm{P,S}} \cdot f_{\mathrm{P,S}}, \tag{3}$$

where $v_{\mathrm{P,S}}$ is the longitudinal or transverse wave velocity, and

$$E = \mathrm{k} \int_0^{\tau} x(t)^2 f(t)^2 \mathrm{d}t, \tag{4}$$

where E is the energy of the radiated signal, $x(t)$ the displacement in time at point of recording, τ the duration of the signal, k is the constant describing the properties and geometry of the media, such as the propagation velocity of a given wave phase, the density and geometry of the wave front.

Equation (4) can be modified for the energy determination to read:

$$E = \mathrm{k}_1 \int_0^T \dot{x}(t)^2 \mathrm{d}t, \tag{4a}$$

where $\dot{x}$ is the velocity vibration component at the point of recording, i.e.

$$\dot{x} = 2\pi f x = \frac{2\pi v}{\lambda} \cdot x. \tag{5}$$

It follows from the above formulas that the acoustic energy released from the stressed rock samples under the given experimental arrangement is proportional to the size of the source of radiation. The shape of the energy-frequency distribution (Eq. 1) also reflects this dependence. This practically means that the above-mentioned shape of the negative exponential distribution (Eq. 1) cannot be expected to describe the distribution of energy released in the whole energy range. The value of the maximum released energy is limited to the sample size.

3. Rock Samples

The study was conducted on granitic rocks exhibiting different fabric features like intensity of the fabric, grain size and microcrack density. Rock samples (sampled in granitoid plutons and crystalline units of the Bohemian Massif, Czech Republic) for geomechanical tests and AE monitoring were cut from the block of an intact rock in three mutually perpendicular directions according to the orientation of rock fabric elements (magmatic banding, joint distribution, foliation or lineation). For each rock type, 3 samples were prepared in each direction, giving a total number of 9 samples. The rock fabric was studied in thin sections by standard petrographic and petrostructural methods. A quantitative analysis of microstructures (grain sizes, shapes and other geometrical characteristics of grains) and of mineral content was carried out by using an image measurement system of thin sections employing SIGMASCAN software (Jandel Scientific, U.S.A.). The original idea for its construction came out from the image measurement method mentioned by Siegesmund et al. (1994). The whole process consists of the following stages – image acquisition, image pre-processing, digitising, measurement, and data analysis (Přikryl, 1998, 2001). Some of the obtained parameters are summarised in Table 1. The rocks investigated can be divided in two groups according to their fabrics:

- quasi-isotropic rocks with different grain size of major rock-forming minerals and diverse microcrack density but constant mineralogical composition (i.e. granites),
- anisotropic rocks with constant grain size and mineralogical composition similar to granites but different intensity of fabric (i.e. orthogneisses).

4. Testing Method

Uniaxial compression tests were carried out under constant stress rate conditions (0.3 kN/s) on samples showing length/diameter ratio 2:1. The axial strain was monitored by coupled LVDTs. All samples were stressed to macroscopic failure.

Table 1. Basic physical, microstructural and mechanical data of rocks under study (adopted from Přikryl, 1998). Mean grain size is expressed as a diameter of the circle occupying the same area as analysed grain. UCS means Uniaxial Compressive Strength. Young's modulus was determined at 30% of UCS

	Dry bulk density [g/cm^3]	Real density [g/cm^3]	Open porosity [%]	Mean grain size [mm]	Volume of quartz [%]	Volume of K-feldspar [%]	Volume of plagioclase [%]	Volume of micas [%]	UCS [MPa]	Static tangent Young's moduli [GPa]
Group I. Quasi-isotropic rocks										
Fine-grained granite RP1	2.613	2.649	1.34	0.128	36	33	26	5	235	58
Medium-grained granite RP7	2.607	2.649	1.59	0.312	41	24	29	6	150	52
Medium-grained granite RP8	2.633	2.665	1.76	0.439	36	31	24	9	140	30
Coarse-grained granite G9	2.560	2.651	4.14	0.641	40	22	30	8	103	28
Coarse-grained granite G8	2.558	2.663	3.97	0.737	41	22	28	9	90	27
Group II. Anisotropic rocks										
Fine-grained orthogneiss RP2	2.644	2.667	0.88	0.139	26	39	13	22	119	47

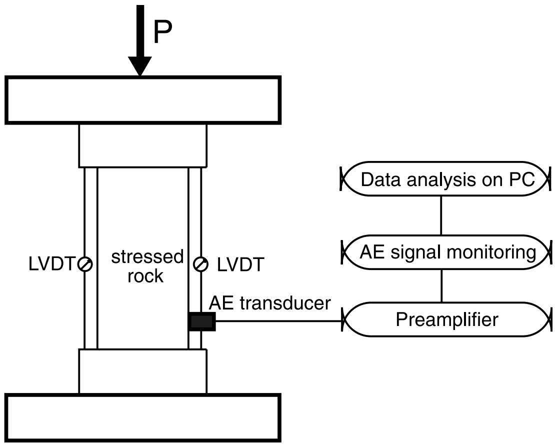

Fig. 1. Experimental set-up of AE detection during uniaxial compression test

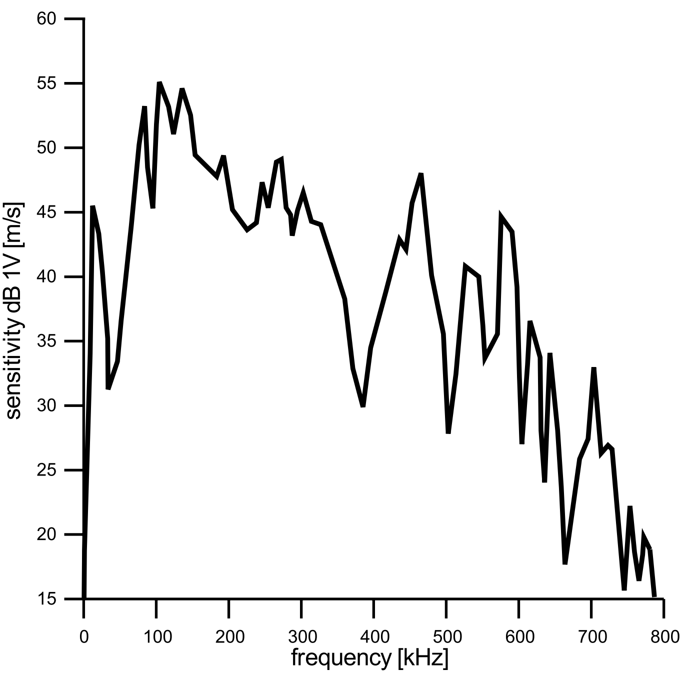

Fig. 2. Amplitude/Frequency response curve of WD transducer (according to the materials of Physical Acoustic Corporation, U.S.A.)

AE was monitored using five piezoceramic transducers fixed to the sample's surface (Fig. 1). The AE sensors employed in this study (WD type, Physical Acoustic Corporation, U.S.A.) possess a wide operating frequency range from 1 kHz to 1 MHz and indicate a maximum sensitivity of the velocity component for the frequency range 50–350 kHz (Fig. 2). This response was determined by using the ''Transient Surface

Wave Technique''. For the experimental set-up adopted when AEs are recorded using ''Face-to-Face Technique'', the frequency range will be wider. The AE sensors were fixed to the sample's surface with the mixture of paraffin and resin.

AE signals were preamplified by an external amplifier and processed by the special interface card SF-41 designed for multichannel recording of acoustic emission signals in a wide frequency and amplitude range (Lokajíček and Vlk, 1994). The card was designed to process analog signals to integrate directed signal to ''zero''. During the loading of the samples all measured data were collected and stored on the hard disc of an IBM-PC computer. AE was recorded at 4 independent channels with different preamplification for each channel (0, 40, 60, 80 dB) because the card SF41 contains only linear preamplifiers. Recording system indicates extreme bits for each channel showing cutting of the signal by extremely high preamplification. According to this extreme bit, it is possible to select a real (:not distorted) value from 4 values recorded by the SF41 card. This approach allows acoustic data to be analysed in a very wide dynamic range (more than 100 dB). For all signals of the acoustic emission, released during the whole loading cycle (up to total destruction of the sample), the value characterising its energy was determined automatically by the recording system:

$$E = \mathrm{k}_1 \cdot \left[\int_0^{T} |\dot{x}(t)| \mathrm{d}t \right]^2 \tag{6}$$

where $\dot{x}$ is the velocity component at the point of recording, k_1 is the constant describing the properties and geometry of the media (such as the propagation velocity of a given phase, the density and geometry of wave front). Each event was analysed regarding its time of occurrence, energy and polarity of the first onset. Processing of raw data is mentioned elsewhere (Rudajev and Lokajíček, 1996).

The limited size of samples facilitates soon observation of reflection from sample's surface. It follows from the sample and P-wave velocity value, that only very beginning of the signal (first 40 μs) is not disturbed by the reflections from samples surface. The remaining part of the signal presents superposition of reflected ultrasonic signal. Based on this assumption, the complete wavelet of the processed signal is proportional to the radiated energy of AE.

Stressed samples were impregnated by the mixture of low-viscosity epoxy resin and fluorescent dye using vacuum technique similar to Nishiyama and Kusuda's technique (1994). Without impregnation, the micro- and macrocracks remain optically translucent and isotropic. The impregnation brings clear distinction between micro- and macrocracks and mineral skeleton. After the procedure, samples were cut into slices along their vertical axis (axis parallel to the applied compression). The slices were observed and photographed under ultraviolet light. Some of the fracture patterns were also observed in a scanning electron microscope (SEM).

5. Results and Discussion

5.1 Grain Size and Microcrack Length Effect

The effect of grain size is demonstrated on AE energy distribution of stressed quasi-isotropic granites (rocks of group I.) exhibiting different grain size. Lokajíček et al.

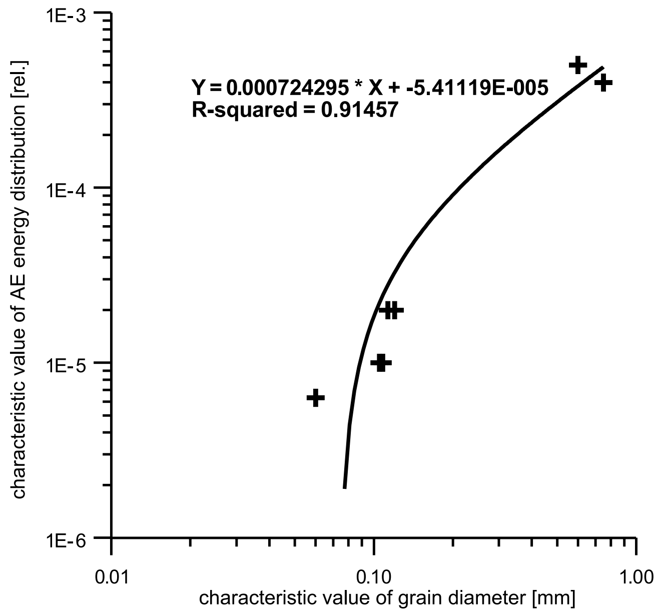

Fig. 3. Correlation between characteristic value of grain size distribution and characteristic value of AE energy distribution (After Přikryl and Lokajíček, 1999)

(1996) argued that characteristic value of the AE energy distribution is proportional to the mean grain size. The results of this study show that the AE energy distribution is more likely proportional to the grain size distribution and to its characteristic value. The increase in characteristic value of grain size distribution (i.e. increase of proportion of larger grains in rock) will change the characteristic value of the AE energy distribution (Fig. 3).

Under the given experimental set-up, where rock samples are compressed by simple uniaxial stress, dominant axial fracturing (extension fractures) occurs (Gramberg, 1989). The mechanical models of rock brittle deformation (Li, 1993; Li and Nordlund, 1995) demonstrated that the axial splitting failure of rocks causes more abrupt failure than the shear faulting. Nevertheless, secondary shearing can develop leading to the formation of overall observable conical patterns or ''en echelon'' cracks array (Olson and Pollard, 1991) during the collapse of the sample. Lokajíček and Vlk (1994) have shown that energy of acoustic emission is proportional to the square of displacement. If one accepts that the rock primarily deforms due to the tensile cracking, axial cleavage fracturing and similar mechanisms then a change in mean grain size of 3-times will produce change in crack area of approximately 10-times and this will result in change of characteristic energy of 100-times (compare Fig. 3). Kusunose et al. (1991) brought first evidence on the effect of grain size distribution on character of AEs. The opening displacement of tensile cracks has been observed to be directly proportional to the crack length or crack area (Hatton et al., 1993; Ayling et al., 1995).

The maximum value of the grain-size distribution is called the typical value of grain size. A pronounced decrease can be observed in the occurrence of grains with sizes smaller than the typical value. This fact is similarly reflected by the AE energy-frequency distribution, in which the decrease of the number of events with lower energies than the characteristic energy value can also be observed. The drop in the frequency distribution of grains larger than typical, and analogously also the drop in the distribution of energetically strong events correspond to the expected event distribution. On the basis of the similarity between the grain-size distribution and the distribution of the AE energy, one may assume that the sources of the acoustic emission (i.e. the points of brittle fracturing of the sample) lie either on grain boundaries or on transgranular cracks.

Rudajev et al. (1994b) have shown that the energy-frequency distribution can be described by a bilogarithmic curve, which almost preserves its own character (shape) during the whole loading cycle (from a stress value equal to 50% of the strength limit of the model sample, when AE events start to occur, up to 95% of strength limit). The maximum value of the energy-frequency distribution can be found in the vicinity of 10^{-1} relative energy units but this value seems to be dependent of the level of the acting stress. This is caused by the fact that stronger grains break at higher stresses and release more energy than the weak ones. It is supposed that the framework of the largest grains disrupt just before the macroscopic failure of the specimen. The failure of large grains at the end of loading correlates with the highest released energies (Fig. 4). This fact corresponds with the demonstrated relationship between typical radiated energy and typical size of contact planes between the grains. The difference between the AE characteristic energy radiated at different stages of loading can cover a range of two to three orders in magnitude.

The above mentioned laboratory experiments have been focused on the investigation of the energy-frequency distribution and proved the precursory character of the stress state of the sample (mainly its total rupture). No significant changes in the shape of this distribution before the total rupture of the sample (close to the marginal deformational stage) were observed.

5.2 Rock Fabric Effect and Fracture Pattern

AE characteristics are also strongly dependent on the bulk rock fabric. This is well-documented on the example of highly anisotropic orthogneiss (rocks of group II.) (Fig. 5). The most pronounced differences were recorded in the AE energy distribution and in the shape of AE cumulative energy curves. This is probably caused by diverse bonding strength of various fabric elements and corresponds to the pronounced anisotropic stress-strain behaviour of the rock. The model of elastic stress distribution (Hawkes and Mellor, 1970; Patterson, 1978) suggests inhomogeneous distribution of stressing in rock specimens. The important factor influencing the correct interpretation of fracture pattern is the scale of observation. When examining typical cone-shaped fragments of loaded specimens, one could mistakenly assume that the shearing is the driving process of sample's failure under uniaxial compression. The microscopic study of stressed and successively impregnated samples revealed, on the other hand, the predominance of tensile fracturing. The type of microfractures is controlled by rock fabric and grain size. In highly anisotropic rocks, the cohesion along grain boundaries is weaker than the strength of minerals. This leads to the development of tensile grain-boundary microfractures. Tensile intragranular fracturing is typical for granites

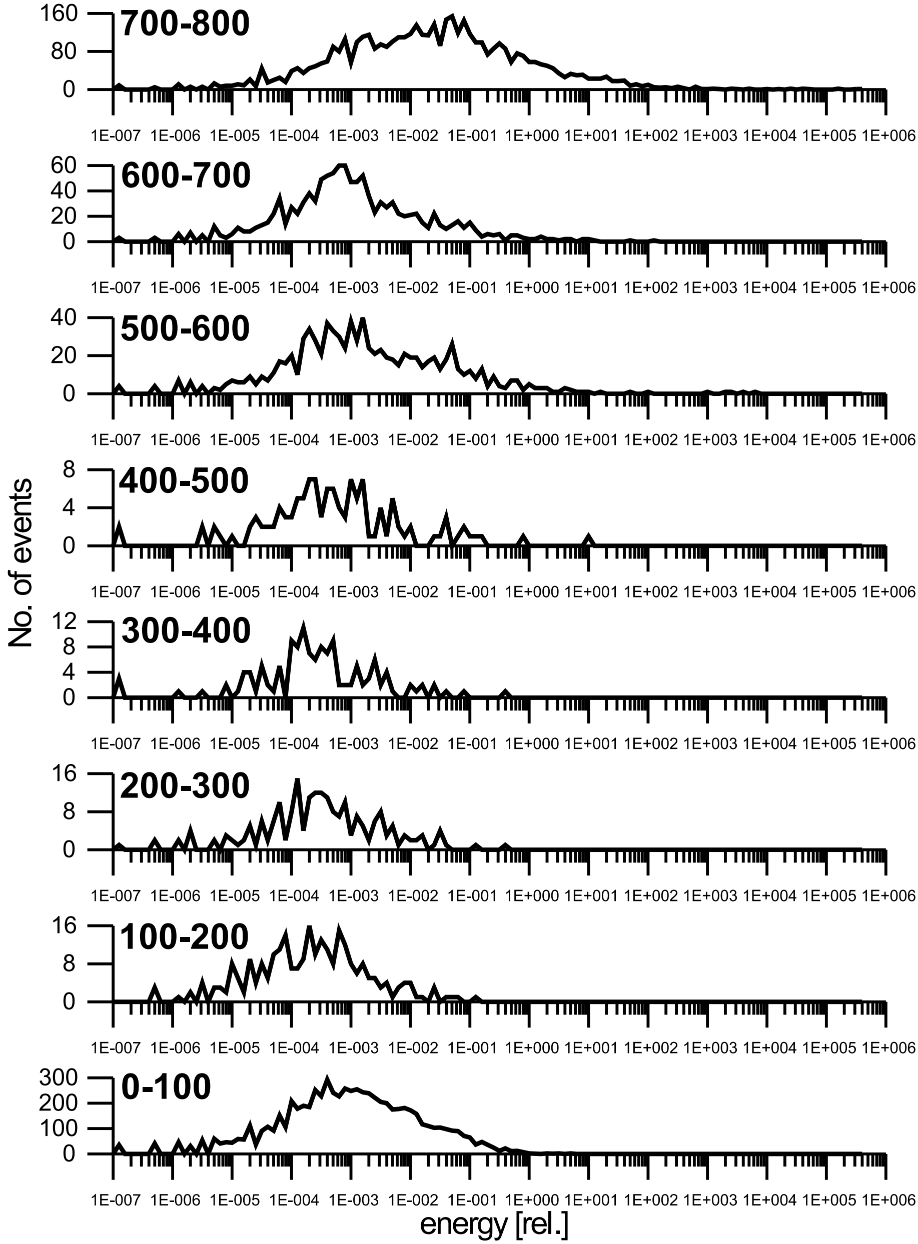

Fig. 4. Series of time dependent energy-frequency distribution curves of orthogneiss (Sample RP2, Specimen 4656 loaded parallel to the lineation). Each graph represents the time interval (that is indicated in seconds in the left upper corner) for which the characteristic value of AE energy was determined (adopted from Přikryl, 1998)

(Fig. 6A). Tightly closed shear fractures occur in anisotropic rocks forming bridges between neighbouring tensile microfractures (Fig. 6B). Such interaction of tensile fractures and favourably inclined micas which are weak in shear is common in rocks

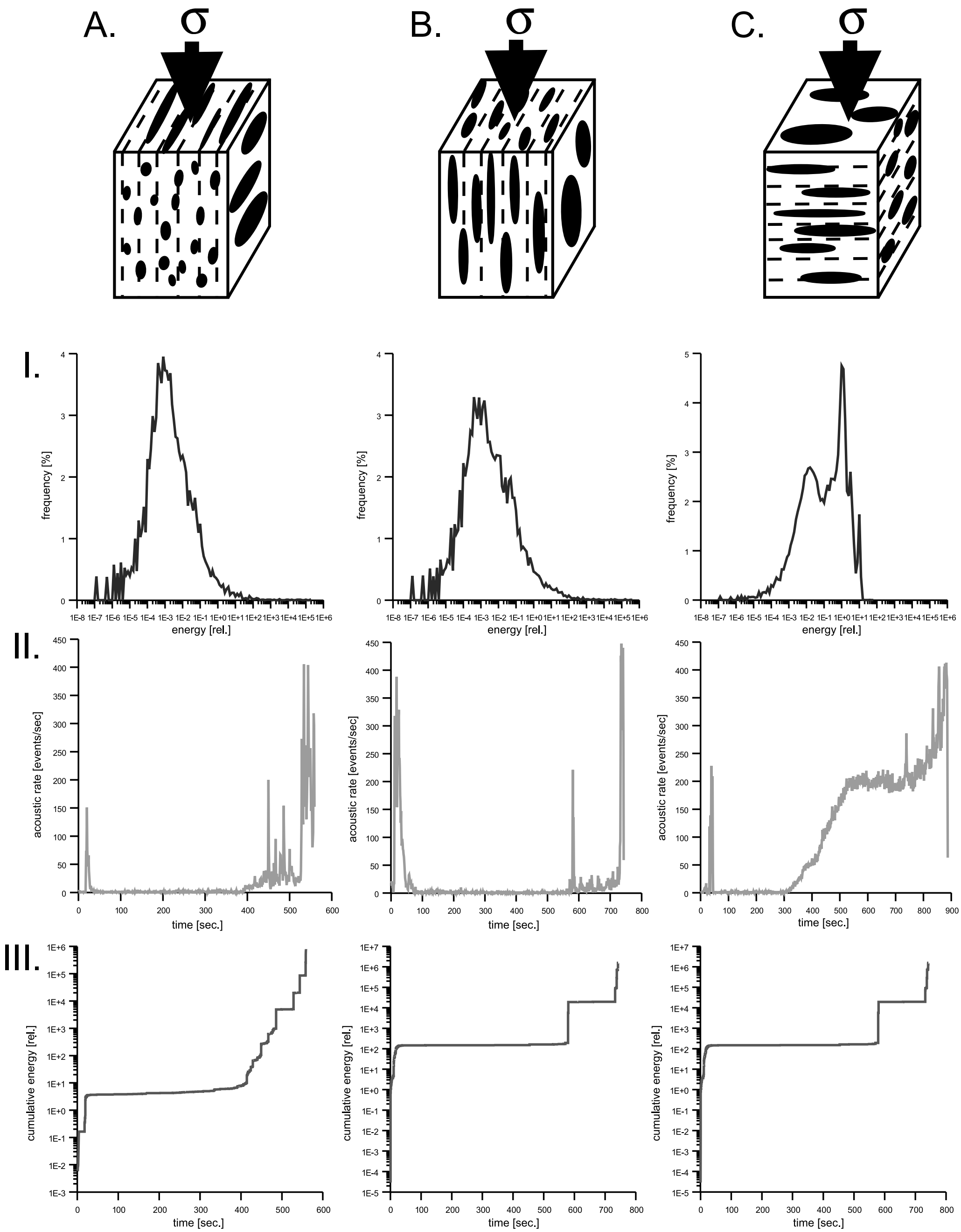

Fig. 5. Effect of sample's rock fabric orientation on the AE characteristics. Example of highly anisotropic rock – orthogneiss. **A** Axial stress was oriented perpendicular to the lineation and parallel to the foliation. **B** Axial stress was oriented parallel to the lineation and to the foliation. **C** Axial stress was oriented perpendicular to the lineation and to the foliation. **I** Frequency of AE energy distribution. **II** Dependence of AE rate on time. **III** Dependence of cumulative energy of AE on time

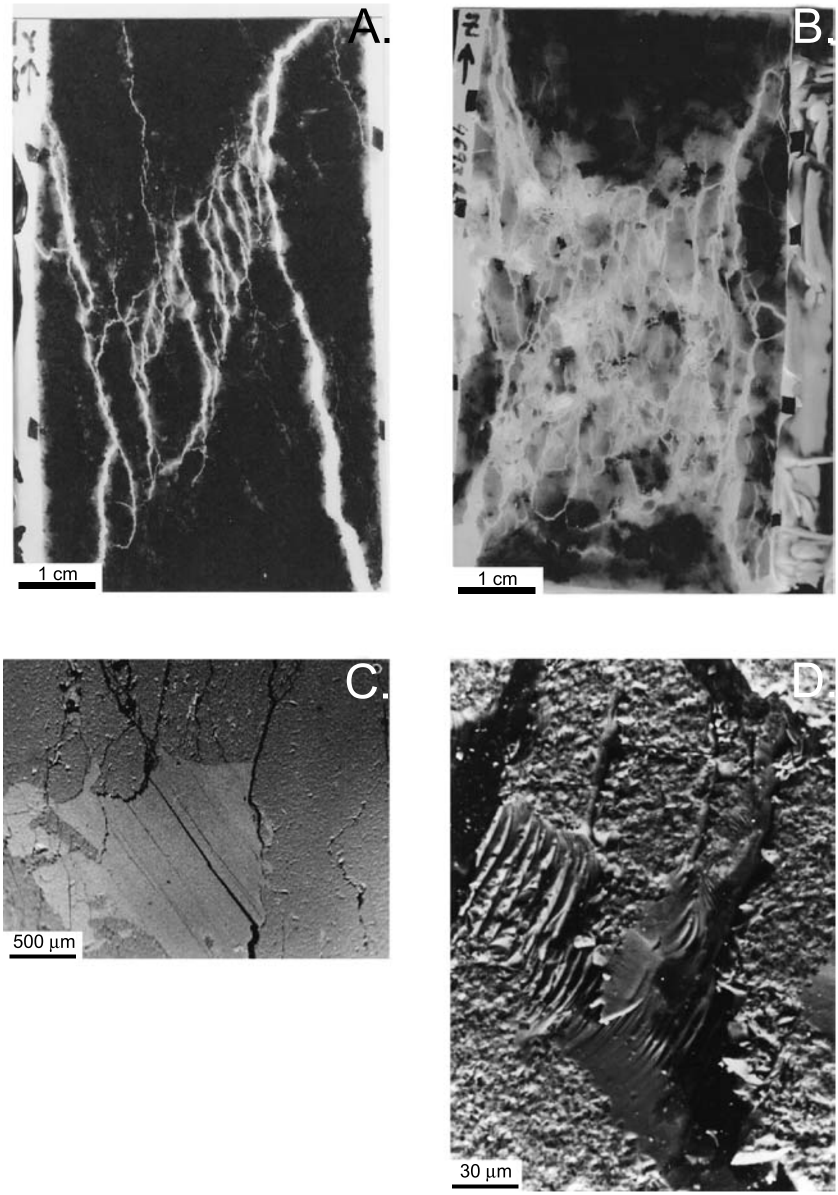

Fig. 6. Microphotographs and SEM images of studied rocks after uniaxial compression tests. **A** Deformation of orthogneiss (Sample RP2), loading direction oriented parallel to the foliation plane. **B** Multigrain fracturing oriented parallel to the loading direction and relatively closed oblique fracture faces that are supposed to propagate as shear fractures (Sample G8, Specimen 4693 loaded parallel to the Z Axis). **C** SEM image of open tensile fractures in quartzofeldspathic matrix connected through closed shear fracture in mica (Sample G8). **D** SEM image of fracture surface phenomena with series of plume markings indicating shock source (fracture nucleus) propagation (Sample G8). Fracture surface parallel to the loading direction along vertical axis of the picture

dominated by quartzofeldspathic matrix (Fig. 6C; compare also Tapponier and Brace, 1976; Wong, 1982).

The deduction of fracture growth is supported by the analysis of the AE signal polarity distribution. The polarity of each signal onset presents a sensible indicator of the movement mechanism on the plane of propagating fracture recorded at the point of registration. The SF41 card automatically captured the polarity of AE signal from the channel with highest preamplification (80 dB). The processing of AEs polarities thus presents mainly statistical task because of limited number of transducers and quasi-random distribution of stress concentrators that are assumed to be a source of AEs. Employed measuring system and data processing allows AEs to be distinguished between groups of minus and plus sign (first-motion) onset. Negative first motions (minus polarities) are from compressional motions associated with the source region moving inwards (i.e. crack closure, pore collapse). Positive first motions (plus polarities) on the waveforms are from the dilatational motions at the source being associated with the source region moving outwards (i.e. crack opening, tensile crack growth). Current measuring system is not capable to reconstruct acoustic events with a more complex radiation pattern, i.e. the double-couple mechanism.

All studied rocks exhibited balanced occurrence of tensile crack growth and grain crushing during loading and the predominance of compressional AE events before failure. The cyclic variation (compare Fig. 7) of tension and compressive events

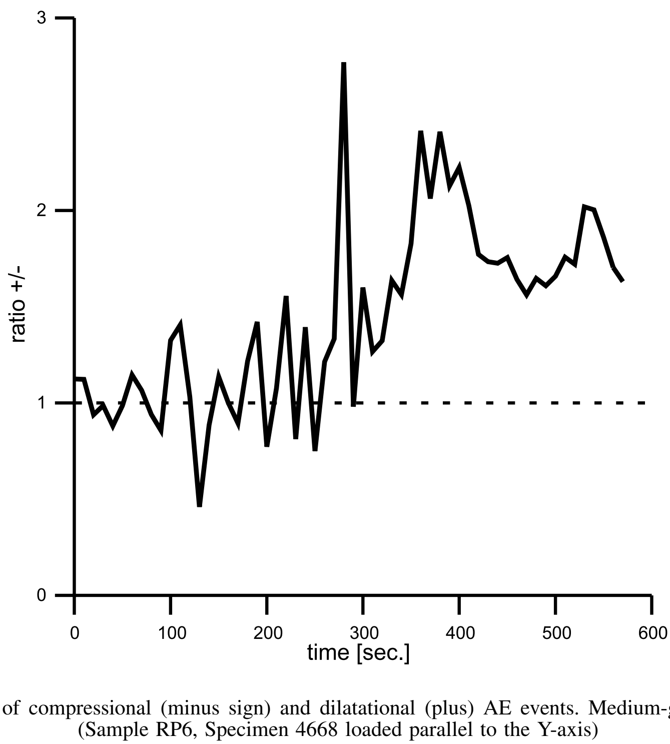

Fig. 7. Ratio of compressional (minus sign) and dilatational (plus) AE events. Medium-grained granite (Sample RP6, Specimen 4668 loaded parallel to the Y-axis)

during uniaxial loading also supports the presence of complex mixed phenomena during fracture growth. The coexistence of tensile crack opening and successive frictional shearing along some fracture planes is documented by several experimental studies (Shah and Labuz, 1995; Zang et al., 1996). The presence of tensile crack opening was confirmed by direct observation of fracture surface by SEM (see Fig. 6D).

6. Conclusions

The study of relationship between acoustic emission and rock fabric revealed three important characteristics:

1. dependence of AE energy on grain size distribution;
2. dependence of AE rate and AE cumulative energy on the anisotropic state of rock fabric;
3. dependence of AE on brittle fracture pattern.

The energy of the AEs depends strongly on the dimension of the contact planes between the grains, where acoustic energy release originates. The dependence of AE energy on the characteristic value of grain size distribution can be described by power series function where $n < 1$. The maximum value of the distribution (characteristic energy) depends on the level of actual stress. The experiments demonstrate that larger grains break at higher stresses and release more AE energy than finer grains disrupted at low stresses. The AEs of loaded rock samples were released from intergranular contacts of grains (grain boundaries) and new formed intragranular micro- and macrocracks (cracks within individual grains). In high anisotropic rocks, the effect of grain size is disguised by the influence of macrofabric. The monomineralic clusters showing shape-preferred orientation result in directional dependence of AE parameters.

The high sensitivity of the AE energy-frequency distribution to grain size (for instance the distribution of the discontinuity areas, where the radiation of acoustic waves is generated) indicates that AE monitoring can be used as a proper non-destructive method to assess the fabric (grain-size and fracture distribution) of the stressed material.

The rock fabric influences resulting fracture pattern. AE monitoring and direct microscopic observation confirmed that tensile crack growth is dominant fracture mechanism of uniaxially stressed rock. Nevertheless, secondary shearing can be found namely in anisotropic rocks and in the form of interconnecting bridges of neighbouring tensile microfractures.

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