ACTA MONTANA IRSM AS CR (1996)
Series A, No.9 (100), 121–130

STRUCTURE ELEMENTS OF ROCKS AND ENERGY–FREQUENCY DISTRIBUTION OF SEISMIC PHENOMENA

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From the seismological point of view, the relation between the occurrence of strong and weak earthquakes serves as a basic characterization of the seismic active regions. It has been proved empirically that this can be described by a negative exponential distribution

$$\log(N) = A - \gamma \log(E)\,, \tag{1}$$

where N is the number of seismic events with the energy $E \pm \triangle E$, $2\triangle E$ is the width of energy class, A (seismic activity) and γ (coefficient of repetition) are the parameters of the distribution. If the energy of the earthquake is classified by the magnitude M, then analogical dependence

$$\log(N) = a - bM \tag{2}$$

is valid.

With the use of the relation between the energy and the magnitude ($\log(E) = c_1 M + c_2$), we will get the relation between the parameters of the distributions (1) and (2):

$$b = \gamma \cdot c_1 \tag{3a}$$

$$a = A - \gamma \cdot c_2\,. \tag{3b}$$

In the first approximation [Rudajev et al. 1982] we can assume that $c_1 = 2$; $c_2 = 2$ and thus for the parameters of the distribution ir holds that $b = 2\gamma$; $a = A + 2\gamma$.

For the comparison of seismic activity – of parameter A or of the a, as the case may be – it is necessary to realize that these values are determined for the events with a different energy value.

The value of a is determined for

$$M = 0 : \quad \log(N) = a\,.$$

For these parameters if holds that

$$\log(E) = c_2 = 2 \qquad \text{(it means that } E = 100\text{)}\,.$$

However the value of parameter A is determined for $E = 1$ and thus its value is larger than that of parameter a, which is also in good agreement with the relation (3).

From the property of a negative exponential distribution it follows that the value of the distribution gradient (so–called coefficient of recurrence) γ or b, as the case may be is indirectly proportional to the mean value of radiated energy (or magnitude) during the time interval under the study. Thus the lower value of the coefficient of recurrence is an evidence of the increasing value of strong seismic events.

An example of the particular application of energy–frequency distribution for rockbursts from Kladno coal mine, recorded by the local seismic network [Růžek 1995], is shown in Fig. 1. The figure shows two time periods with the same duration but differing in the value of the released amount of seismic energy. The time dependence of cumulative seismic energy released is presented in Fig. 2; it is evident that during the first quarter of the year 1995 the seismic energy release is higher (and thus the average energy of one rockburst is increasing) which is reflected in the value of the coefficient γ. This fact is in good agreement with the above mentioned dependence of negative exponential distribution. Fig. 2 shows the two different shapes of seismic energy flow computed by different methods of energy determination. In the upper part of the figure the energy is determined according to the definition – by the integration of the power of the amplitude of the velocity component. The lower part of the figure shows the energy flow determined by a simplified approach – by the power of the integral value of the velocity component. Although the numerical values of both computed components slightly differ, the course of seismic energy release is conserved. In the presented paper the shape of energy–frequency distribution (determination of maximum number of events and maximum energy) is analysed on the base of absolute values of energy released.

The simplified approach to energy calculation (lower part of Fig. 2) was executed by the hardware of the measuring system used for the study of acoustic emission originating during the loading of rock samples, as it will be discussed later.

The negative exponential distribution does not describe the occurrence of rockburst in the whole energy range under the study (this fact is evident with both examples shown in Fig. 1). The decrease in the number of seismic events with low value of energy is very often explained by the insufficient sensitivity of the measuring apparatus and also by the unfavourable signal to noise ratio, which decreases the identification of all seismic events [Slavík et. al. 1992].

Very often deviations from the theoretical distribution in the area of strong events are observed. These deviations are analysed for tectonic earthquakes by [Kárník

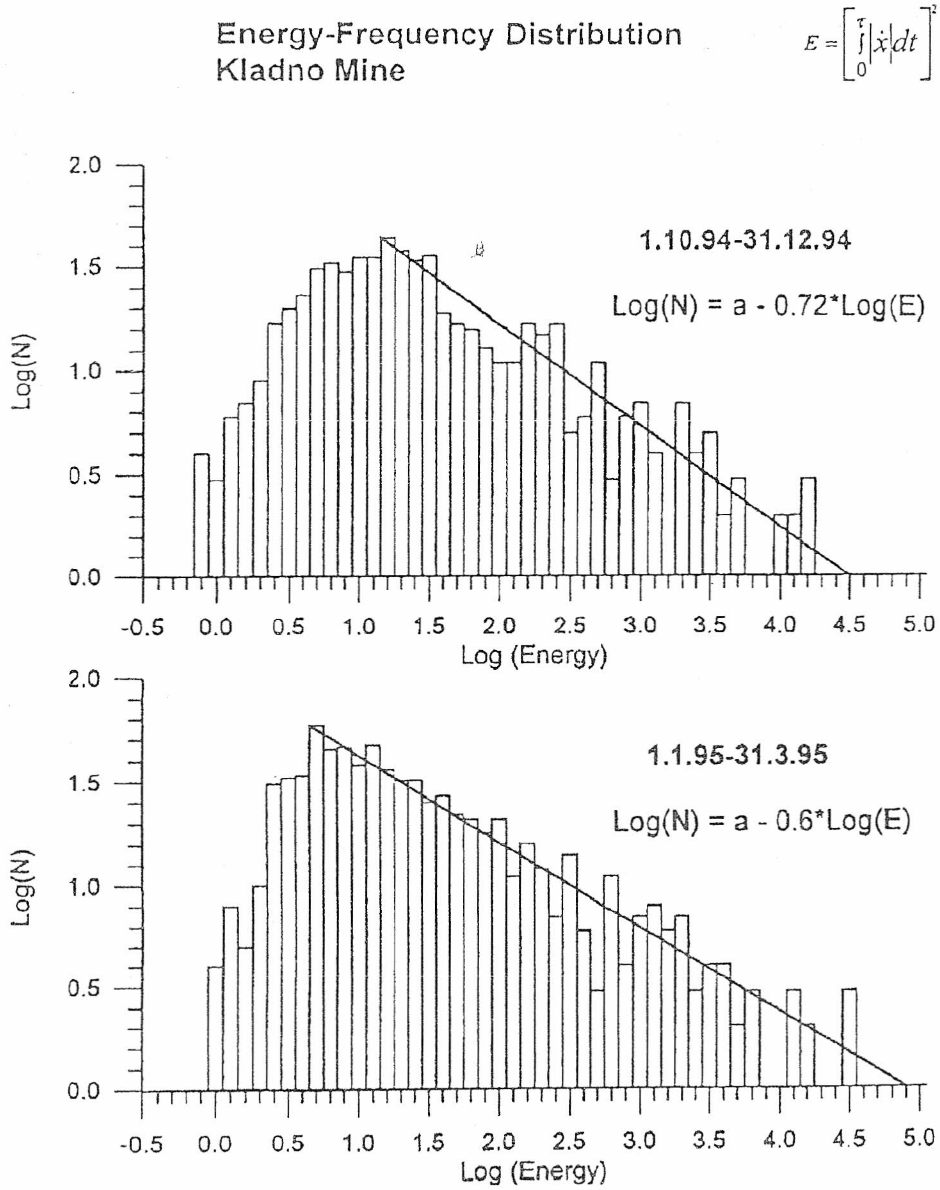

FIG. 1. Energy–frequency distribution of induced seismic events from Kladno coal mine basin determined for two different time periods.

1992]. A dual law of distribution, which describes the distribution of rockburst occurrence in the whole energy range (so–called bimodal distribution) was explained also on the basis of different mechanisms of individual rockbursts and their position according to [Kijko et al. 1985; Lasocki 1992].

The quantity of seismic energy release is connected not only with the physical properties of the fractured rock media (mechanical modules, strengths, cumulated deformation energy) and with the time function and dynamics of the foci (fracturing

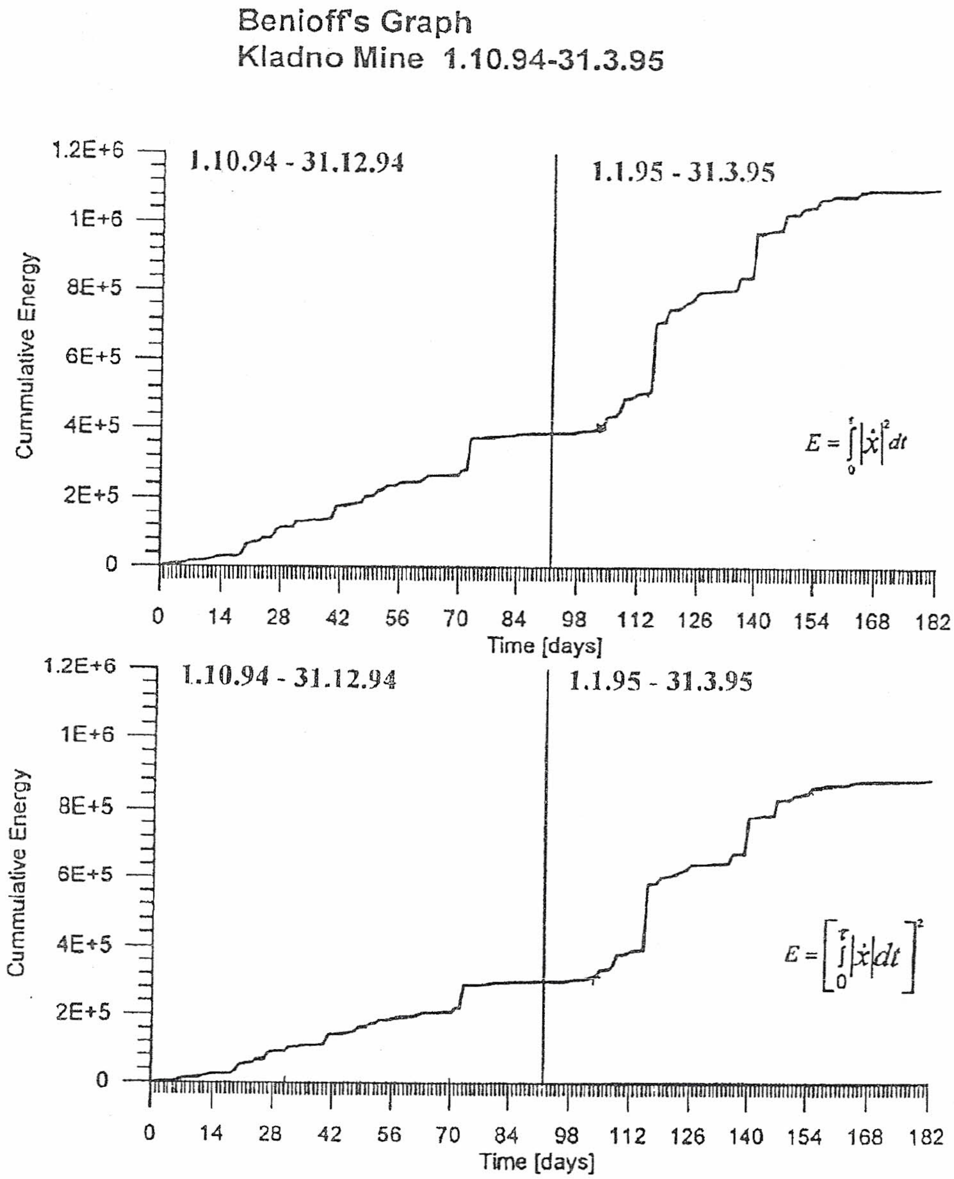

FIG. 2. Time dependence of cumulative seismic energy released computed by means of two different method of energy determination.

velocity and duration, stress drop in the foci) but also with the size of the seismic foci, mainly with the dimension of the dislocation plane on which the irreversible seismoactive deformation occurs. The rock massif is a discrete medium, where it can be expected that the origin of seismoactive fracturing is mainly connected with weak areas, mainly on the plane of the discontinuity. The distribution of the size of these planes of discontinuity in the rock massif according to the above mentioned hypotheses should influence also the quantity of seismic energy released.

According to the linear dimension, the planes of discontinuity can be divided e.g. into 4 orders [Rac 1974].

1. order ($10^2 - 10^5$ m) dislocations (fractures) of regional geological structures
2. order ($10^{-2} - 10$ m) dislocations in the inner structure of the rock massif
3. order ($10^{-4} - 10^{-2}$ m) discontinuity of the mineralogical and petrographical character of the rock media
4. order ($10^{-8} - 10^{-4}$ m) inhomogeneities in the crystallic network.

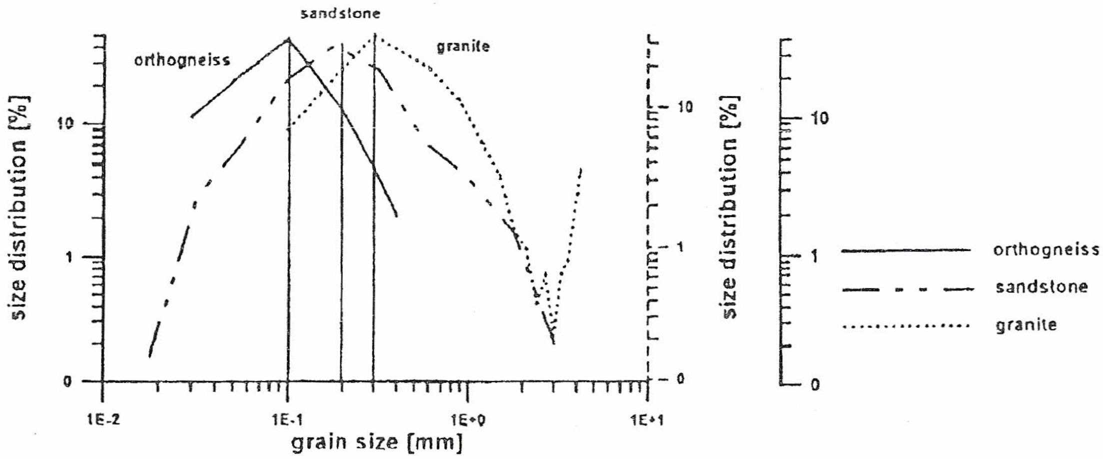

FIG. 3. Grain size distribution of three different types of rocks: orthogneiss, sandstone, granite.

The area of the rockburst research is influenced mainly by the dislocations of the second order. To elucidate the shape (dependence) of energy–frequency distribution on the basis of the relation between the amount of seismic energy released and the dimensions of the planes of discontinuity of the media, a laboratory study of acoustic emission originating during the uniaxial loading of rock samples was carry out. Dynamic characteristics of radiated acoustic signals (frequency, energy) should be influenced mainly by the discontinuities of the third order. Due to this fact, the rock samples under the study were subjected to the precise petrographical analysis. Three types of rock samples with different grain sizes of the minerals were studied: orthogneiss, sandstone (from Kladno rockburst area) and granite. The results of petrographical analysis are displayed in Fig. 3 in the form of the diameter of the grains (in the analysis the grains were assumed to have a spherical shape). The sample of the orthogneiss, where the typical grain size was 0.1 mm displayed the finest structure, the sandstone had the typical value of grain size equal to 0.18 mm and granite equal to 0.3 mm. With all three types of rock samples the distribution has a similar shape and tends to the normal logarithmic distribution. The samples of orthogneiss and granite had the cubic shape and dimensions of $10 \times 10 \times 10$ cm. The sandstone samples had the block shape, with the base of 10×10 cm and the height of 20 cm (the acting force was perpendicular to the sample base). For the recording of acoustic emission, a broad–band digital measuring system was utilised, which was based on the newly developed interface card designed for multichannel recording of acoustic emission signals in a wide frequency and dynamic range. The card allows us multichannel recording, processing and on-line display of acoustic emission activity. The recording system had a constant amplification in the frequency range from 10 kHz to 1 MHz, i.e.in the range of the recorded signals. The piezoceramic transducers were assumed to record the velocity component of the acoustic wave (with the same sensitivity) in the above mentioned frequency range. All samples were loaded with constant stress rate up to their failure. The multichannel recording system makes it possible to automatically determine the energy value of each acoustic emission event according to the formula:

$$E = \left[\int_0^T |\dot{x}|\ \mathrm{d}t\right]^2 , \qquad (4)$$

where t is the duration of the acoustic emission event, $\dot{x}$ velocity component of the recorded acoustic wave.

The inaccuracy of the above mentioned relation with regard to the commonly known physical definition of energy was analysed and discussed by [Lokajíček et al. 1995].

$$E = k \int_0^T |\dot{x}|^2\ \mathrm{d}t\,. \qquad (5)$$

With regard to the fact that not only the shape of energy–frequency distribution is analysed (in the presented paper the absolute values of released energy are given), the simplified determination of energy (Eq. 4) is possible (see Fig. 4). The position of the maximum number of seismic events of the same energy class and also the value of the maximum energy released is preserved.

The shape of energy–frequency distribution of recorded acoustic emission events obtained for three different types of rocks is shown in Fig. 5. It was found that with all samples their distribution tends to the logarithmic normal distribution. Characteristic energy values of radiated signals were determined to be:

8.3×10^{-13} [J] for orthogneiss
4.0×10^{-12} [J] for sandstone
6.6×10^{-11} [J] for granite,

it means that they differ nearly by one order of magnitude (in comparison with the grain size, where the typical values of grain size distribution differed two or three times with respect to the sample with the finest grains. The decrease in energy–frequency distribution in the direction to lower values of energy, with regard to the sufficient sensitivity and good recording quality of recording systems, cannot be explained by their insufficient sensitivity, as in the same energy interval where there is a decreasing part the distribution with granite, there is also a rising part of energy–frequency distribution for sandstone and orthogneiss. It is evident that this phenomena are connected with the grain size distribution and thus with the contact planes between the grains. Two significant conclusions can be deduced from the above mentioned experimental results:

- acoustic emission of loaded rock samples radiates due to the mutual shear displacement of grains – there is no inner fracturing of grains

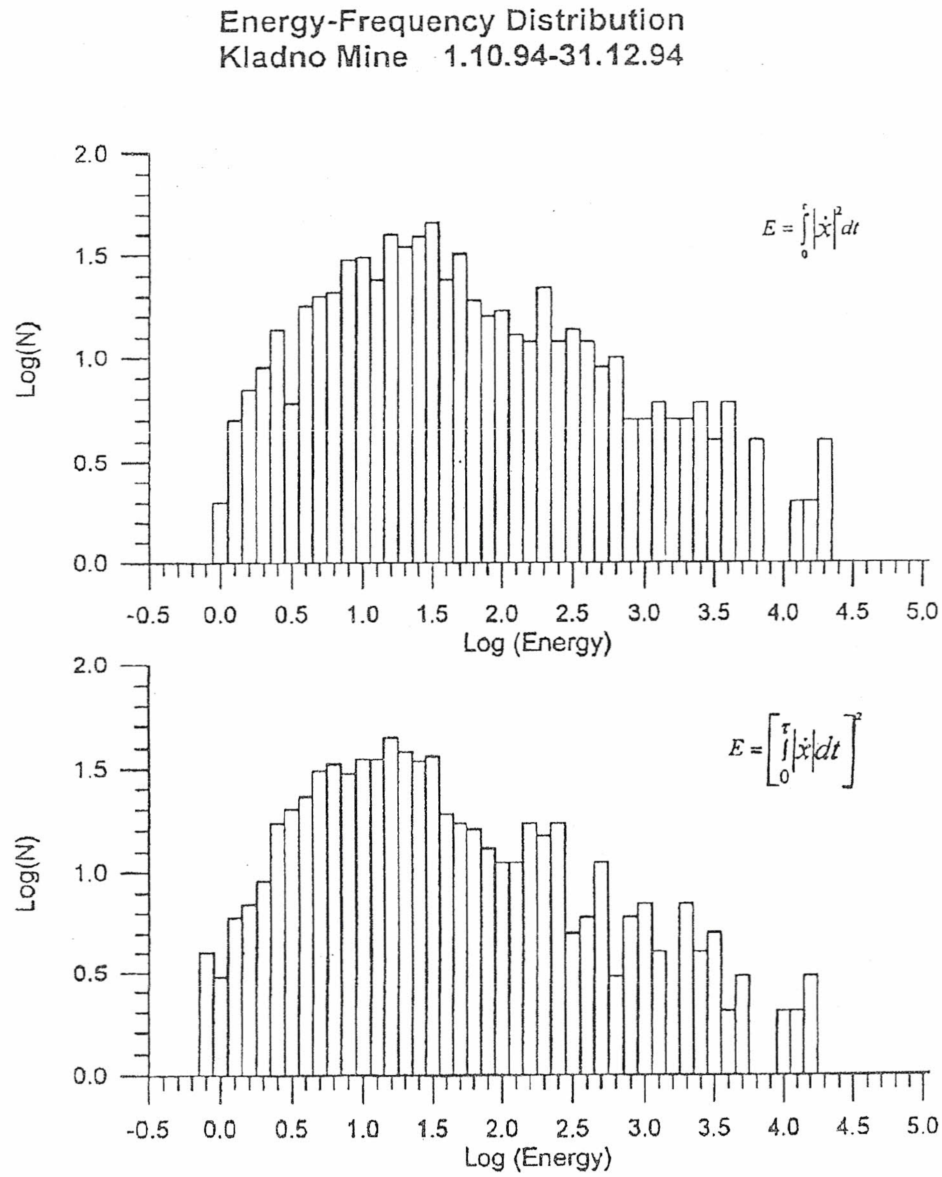

FIG. 4. Energy–frequency distribution computed by two different methods of energy determination for the time period 1.10.94 – 31.12.94.

– energy of radiated acoustic emission signals is very sensitive to the grain size (sensitivity is higher by one order of the magnitude), which follows from the relation between the energy of radiated signal and the plane size of dislocation (there is no linear dependence).

Under laboratory conditions the maximum value of released seismic energy from rock sample is dependent on the maximum size of the sample. With orthogneiss and granite the maximum value is nearly the same, equal to 1×10^{-6} [J] and for

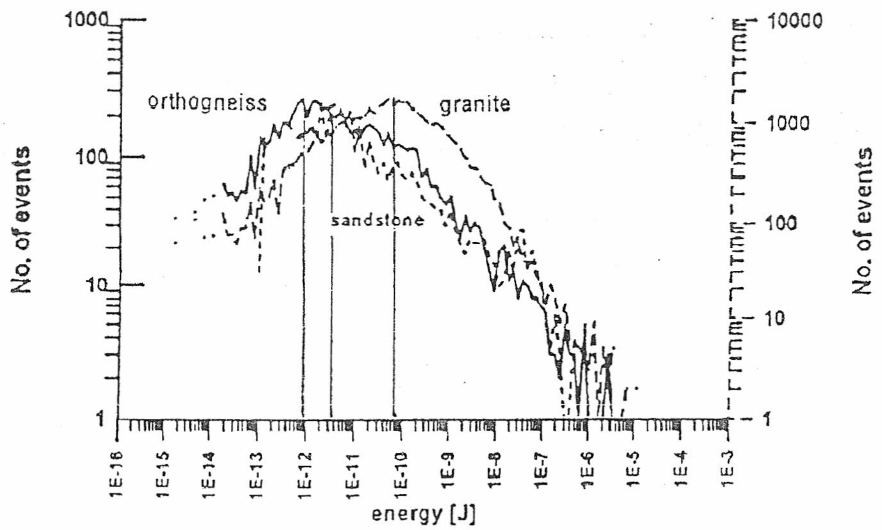

FIG. 5. Energy–frequency distribution of acoustic emission from different rock samples.

sandstone is slightly higher (the volume of the sample was tree times higher) – equal to 3×10^{-6} [J].

The maximum possible energy released of rockbursts is limited by the thickness of sedimentary overburden layers, which reach the value of up to 40 m [Přibyl, Rudajev 1969]. By the application of the relation empirically determined for Ostrava coal mines [Kalenda 1995], the maximum possible value of released energy could reach approximately the value of 10^6 J. This value was not attained during the monitored half–year time interval. By the conjunction of laboratory and field results, it si possible to determine the regressive relation between the linear dimension of the foci (source of radiation) Y and the amount of seismic energy released E, see Tab. 1.

TAB. 1

grain size (Y) [mm]	0.1	0.18	0.3	40000.
energy (E) [J]	8.3×10^{-13}	4.0×10^{-12}	6.6×10^{-11}	1.0×10^{6}

Thus

$$\log Y\,[\mathrm{mm}] = 0.31\,\log(E)\,[\mathrm{J}] + 2.74\,. \tag{6}$$

The graphical representation of equation (6) is presented in Fig. 6, where the energy of acoustic emission signals is determined by the maximum of energy–frequency distribution function, so–called characteristic value of energy. The energy value of 10^6 J is given by the maximum observed energy of rockbursts at the Kladno mine region, which can be released due to the tectonic structure [Přibyl, Rudajev 1969] from the sandstone layer with maximum thickness of 40 m. By $\triangle$ the energy value representing the characteristic energy value of seismic events equal to 30 J ($\log(E) \cong 1.5$) is denoted. From this graph it follows that the typical dimension

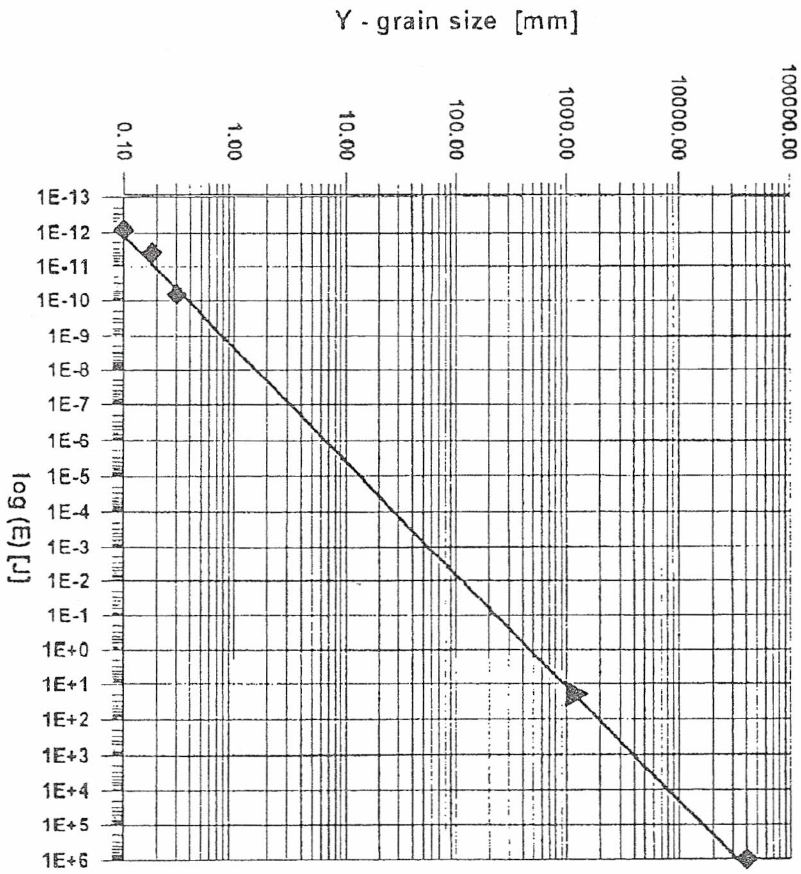

FIG. 6. Empirical relation between released seismic energy and different dimensions of rock elements.

of tectonic faults, which are responsible for the radiation of seismic energy, is approximately 1.5 m. This result is in good agreement with the observed tectonic fracturing of this area.

From the obtained results a very important methodological instruction follows, namely that the parameters of energy frequency distribution (A, γ, or a, b, as the case may be) must be determined, for which the energy interval (or the magnitude interval) of the negative exponentional distribution was calculated and which was the whole energy range of recorded signals.

ACKNOWLEDGEMENTS:

A portion of this work was supported by Grant Agency of the Czech Republic, No. 205/95/0263 and by the Grant Agency of Academy of Sciences of the Czech Republic No. 34624.

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