# Correlation analysis of ultrasound emission foci in loaded granites and migmatities

Veverka J., Rudajev V., Lokajíček T.

## Introduction

The problem of building underground deposits of radioactive substances and toxic waste is topical at this time. In connection with this problem, it is also important to know the long-term stability of the underground spaces. For this purpose, it is necessary to monitor the deformation properties of rocks and, in particular, the course of their deformation and assessment of the critical state of stress (Hirata et al., 1987; Lockner, 1992; Lokajíček et al., 2002; Rudajev et al., 1996, 1997, 2000, Vilhelm et al., 1997).

In loading rocks (and also building structures) once the critical state of stress has been reached, only a certain part of the rock massif become deformed (Veverka et al., 2000; Lockner and Byerlee, 1991). The identification of this predisposed volume before total failure is important with regard to measures, which can be taken in the affected part itself in order to reduce the danger of sudden release of deformation energy (Číž and Rudajev, 1999; Zang et al., 1996, 1998).

Past research has disclosed that the distribution of locations with the highest concentration of foci changes during loading (Veverka, 2000). So far, however, the problem of the influence of the separate regions on one another and their causal connection has not been studied. This question is analysed in this paper.

The purpose of this study is to provide a prognosis of the locations of ultrasound signals, which are generated by brittle microfracturing caused by loading rock samples. By studying the migration of ultrasound signal foci, especially their clustering in limited parts of the rock sample, it is possible to estimate the place and/or area of future total failure. The estimation of this critical place is based on determining the cross-correlation of occurrence of ultrasound signals in various parts of the rock sample, and on its interpretation with regard to their effects on one another. It is also the purpose of this study to assess the effect of the loading rate of rock samples on the spatial distribution of microfracturing foci and their influence on one another.

This paper deals with developing methods of assessing the influence of the regions on one another. The developed algorithms are applied to actual measurements. The results of this interpretation will contribute to solving the problems of forecasting the most endangered, i.e. the future place of total failure.

## Processing of ultrasound emission data

The method of correlation analysis was used in processing the ultrasound emission data. In order to assess the effect ultrasound signals have on one another in various parts of the rock sample, the rock samples was in each case divided into several segments, usually by three mutually perpendicular planes into 8 segments of the same size. The rock samples had the shape of cylinders, 5 cm in diameter and 10 cm in height, so that the separate regions were formed by segments in the shape of a quarter cylinder, 5 cm in height and 2.5 cm in radius. The segments were number in the same order, so that in a right-handed Cartesian system, the origin of which is in the centre of the base, Segment 1 has both co-ordinates x, y negative, and

Segment 2 x positive and y negative, Segment 3 x negative and y positive, Segment 4 both co-ordinates positive, and in all cases the z co-ordinate ranges from 0 to 5. Segment 5 lies on Segment 1, 6 on 2, 7 on 3, and 8 on 4, the z co-ordinate of these segments being in the interval 5 – 10.A time sequence of pulses, whose foci were located within the segment, was constructed for each segment. This method yielded 8 time sequences of ultrasound pulses.

The sequence in the i-th segment was constructed from the time window, length $T_m$ (the *m*-th interval defined by its beginning and end) and the total loading time is $T_c$. This window, $T_m$ in length, is divided into N time subintervals, length $\Delta t$ $(N = T_m/\Delta t)$ in which a particular number of events occurred. This yields sequences $x_i^m(n)$, where the segments are marked $i = 1, 2, \ldots, 8$, the interval is marked *m* and the sequence elements $n = 1, 2, \ldots, N$. The effect on the occurrence of ultrasound signals in the separate segments was assessed by cross-correlating the appropriate sequences. The cross-correlation coefficients were determined from the relation

$$R_{ij}^m(k) = \frac{\sum_{n=1}^{N}\left[\left(x_i^m(n) - x_i^m\right)\left(x_j^m(n+k) - x_j^m\right)\right]}{\sqrt{\sum\left(x_i^m(n) - x_i^m\right)^2 \sum\left(x_j^m(n) - x_j^m\right)^2}}$$

where

| | |
|---|---|
| $m$ | is the *m*-th time window, length $T_m$, defined by its beginning; |
| $x_i^m(n)$ | is the *n*-th element of the *i*-th sequence appropriate to the *i*-th segment and *m*-th window; |
| $x_i^m$ | is the average of the *i*-th sequence of the *m*-th window; |
| $x_j^m(n)$ | is the *n*-th element of the *j*-th sequence appropriate to the *j*-th segment and *m*-th window; |
| $x_j^m$ | is the average of the *j*-th sequence of the *m*-th window; |
| $R_{ij}^m(k)$ | is the cross-correlation between the *i*-th and *j*-th sequence of the *m*-th window; |
| $k$ | is the correlation step; |
| $i, j$ | are the number of segments, $i, j = 1, 2, \ldots, 8$. |

Time windows $T_m$ and $T_{m+1}$ tied in with one another with a running step of $\Delta_m$ ($\Delta_m << T_m$).

The foci of ultrasound signals were assigned to the separate sample segments according to their location. The location of the ultrasound signals assumed a homogeneous and isotropic medium ($v_p$ = const.) and was determined from the first arrival times of P-waves at the transducer. All computations were automated, and software was developed for locating the ultrasound emission and for the correlation analysis.

**Methods of laboratory experiments**

Samples of granites and migmatites, which were subjected to uni-axial pressure under various loading rates were studied (Rudajev et al., 2002; Veverka et al., 2001). The total loading time $T_c$, i.e. the time interval between the beginning of loading to total failure, was varied over several orders: from ten minutes (short-term tests) through 100 to 1000 minutes (medium-term tests) up to 10000 minutes (long-term tests).

The deformation of rocks (longitudinal and transverse), the magnitude and rate of loading were measured during the experiments, and the ultrasound emission was monitored. The configuration of piezo-ceramic transducers was chosen optimally with regard to the possible location of the ultrasound signal foci.

**Experiment – Granites**

The granite sample from the Vitkov quarry were loaded for several different time intervals, ranging from the shortest loading period, i.e. ten minutes, via one hundred and one thousand minutes, up to the period of longest loading, which lasted about ten thousand minutes.

Short-term tests:
Signals are generating practically in the whole volume of the sample and have no effect upon one another. The total number of signals is relatively small, which corresponds to the fact that the rock reacts only to the acting force without its structure being involved. No rheological processes are generated (Fig. 1).

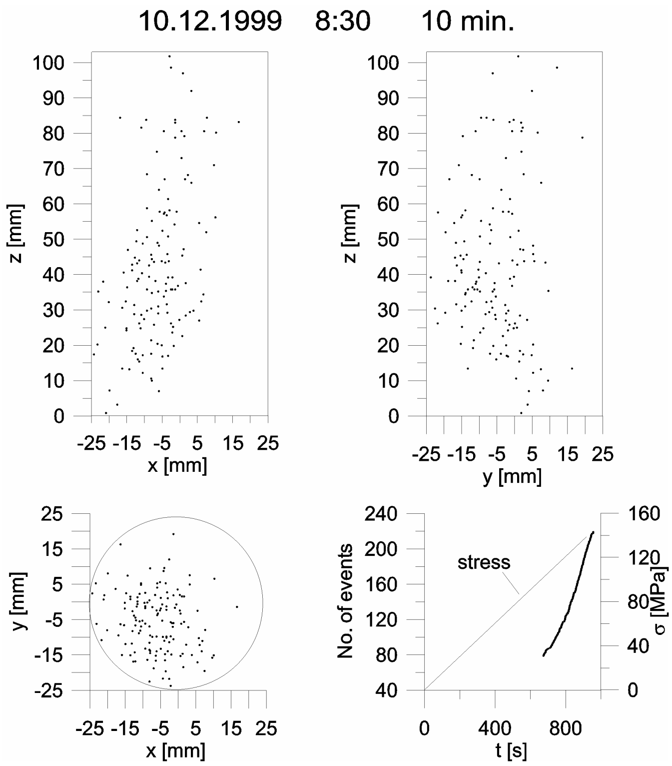


Fig. 1. Graphs of ultrasound emission foci in granite loaded for a period of 10 minutes, and cumulative graph of the number of events as a function of time and loading.

Medium-tem tests
The effect of rock structure on the occurrence of ultrasound signals can be observed beginning with the medium-term tests, i.e. if the loading lasted for 100 or more minutes. The first more significant correlations are observed at a load of 95% $\sigma_{max}$. The maximum number of signals was concentrated in a single segment, No. 3. These signals from Segment 3 preceded the signals from neighbouring Segment 4. During the last stage of loading (99 – 100% $\sigma_{max}$) this correlation vanishes, and the signals are generated independently, the maximum occurring in Segment 3 where total failure occurred (Figs 2 and 3).

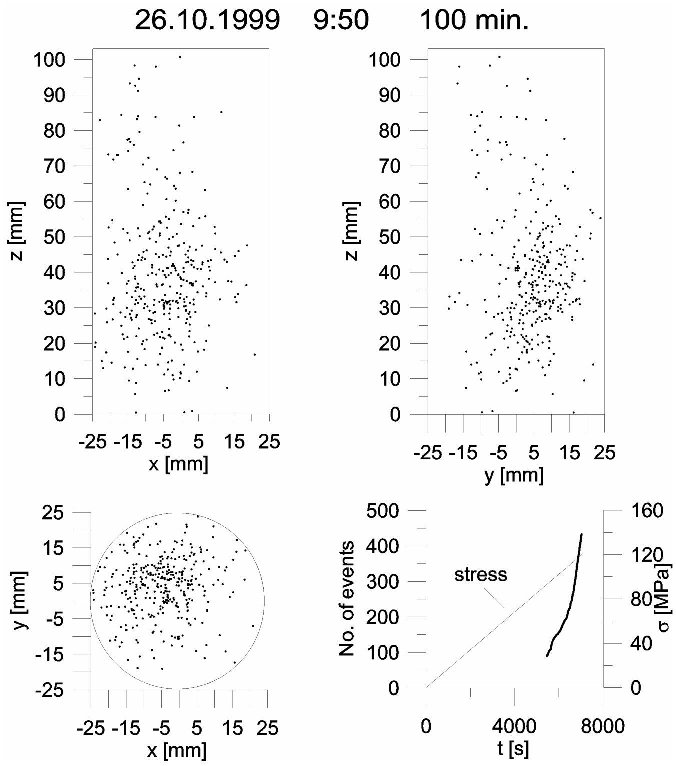


Fig. 2. Graphs of ultrasound emission foci in granite loaded for a period of 100 minutes, and cumulative graph of the number of events as a function of time and loading.

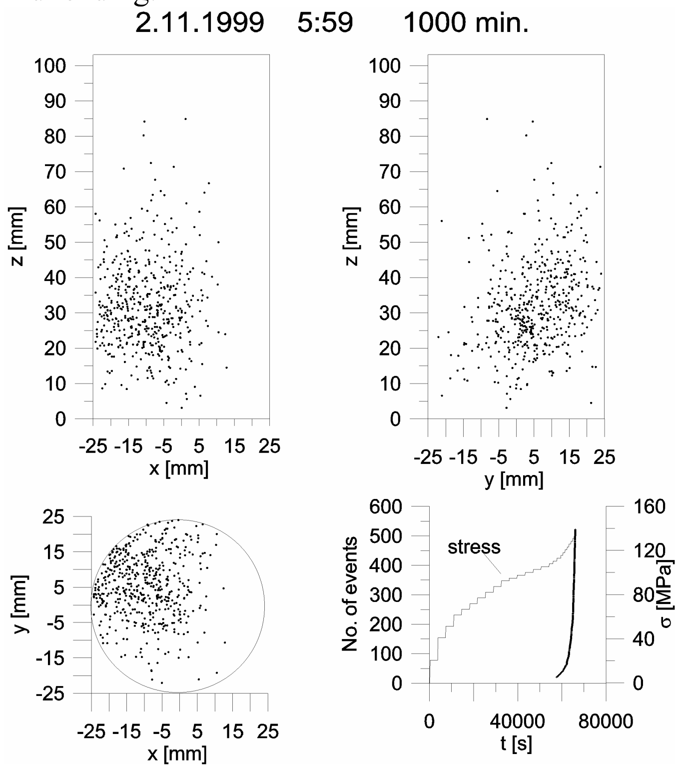


Fig. 3. Graphs of ultrasound emission foci in granite loaded for a period of 1000 minutes, and cumulative graph of the number of events as a function of time and loading.

Long-term tests

During these tests, the duration of which was in the order of 10 000 minutes, signals are generated distinctly only when the load exceeds 90% $\sigma_{max}$. The occurrence of he signals is mostly concentrated into a single segment. During the 91-96% $\sigma_{max}$ loading stage the cross-correlation of the occurrence of signals in his segment with the signals generated in the segment above is increased. However, this concentration vanishes if the load is 97% $\sigma_{max}$ and over. The signals are generated spontaneously in the segment where total failure has occurred, see Fig. 4 (Veverka et al., 2002, 2003).

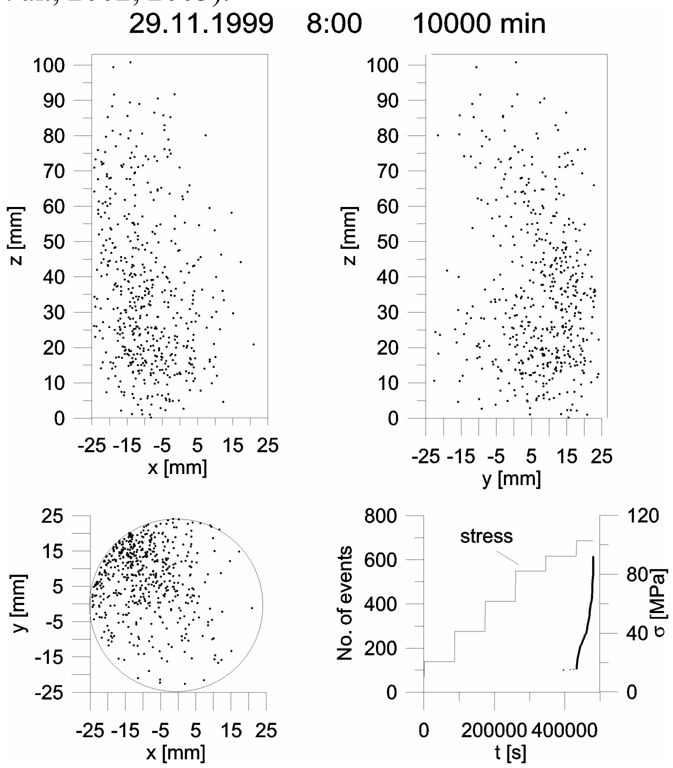


Fig. 4. Graphs of ultrasound emission foci in granite loaded for a period of 10000 minutes, and cumulative graph of the number of events as a function of time and loading.

**Experiment – Migmatites**

The ultrasound emission data were analysed on two samples of migmatites collected at the Skalka locality (a locality being considered for a radioactive waste deposit). Both samples were loaded in the medium term: one for 120 minutes (migmatite 6), the other for 1020 minutes (migmatite 7). The ultrasound emission in both samples began to occur around 50-60% $\sigma_{max}$.

In migmatite 6 the locations of ultrasound signals developed in very much the same way as in the loaded granites from the Vitkov quarry in the Karlsbad pluton. Around 95-96% $\sigma_{max}$ increased correlation of ultrasound signals was observed in segments with the largest number of events. The occurrence of the events in the lower and upper parts of the studied sample was observed to be independent of one another (Fig. 5).

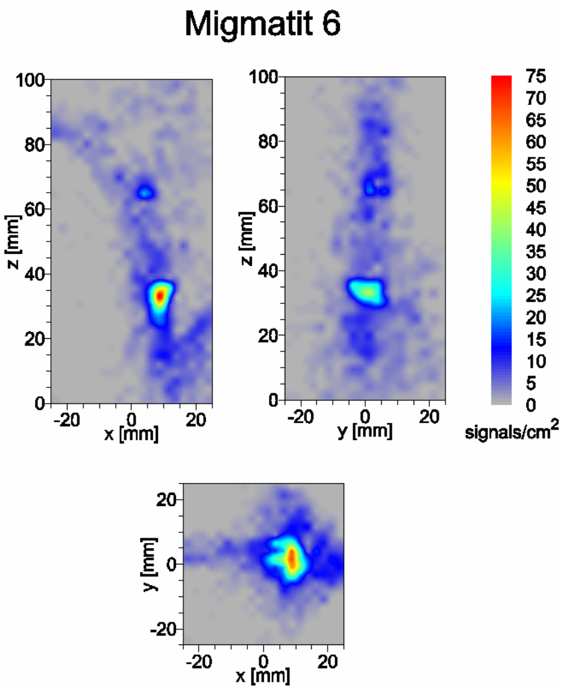


Fig. 5. Distribution of foci of occurrence of the ultrasound emission (events/cm$^2$), migmatite 6.

In migmatite 7 the number of located events went up to 20 000. Cross/correlation analysis was applied, which also took into account the higher coefficients, and it was found that, under increased frequency of events, or above all during the final deformation phase, the values of the cross-correlation coefficients increased also in higher locations. This overall image of the cross-correlation coefficients may also contribute to estimating rock instability, or provide information on the increased frequency of ultrasound emissions (Fig. 6).

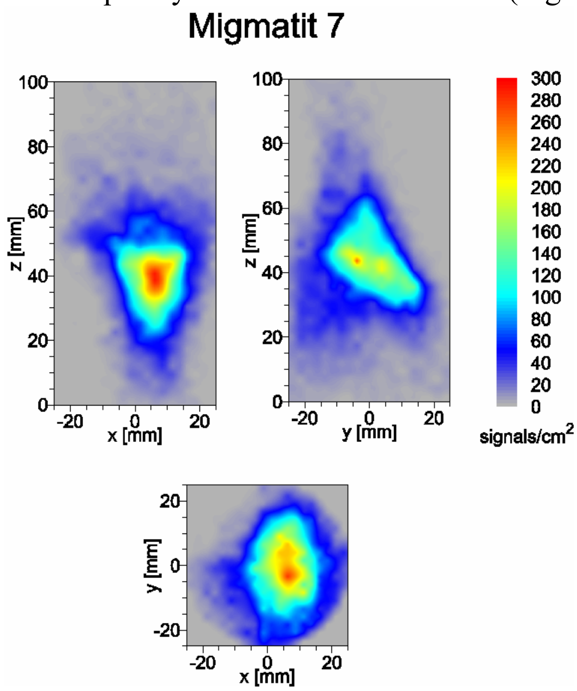


Fig. 6. Distribution of foci of occurrence of the ultrasound emission (events/cm$^2$), migmatit 7.

## Conclusion

The purpose of the study was to determine the locations of increased occurrence of ultrasound signals (of brittle microfracturing) which are generated under various rates of loading of rock samples, their migration in dependence on the acting stress and, in particular, to assess the effect their origins have on one another. Based on determining the locations of increased concentrations of ultrasound signals, as well as the way in which they are affected, the parts of the rock samples, in which total failure occurs were determined, and the time at which such total failure occurs was estimated. Correlation analysis of ultrasound signals, generated in various parts of the rock sample, was applied in determining the effect of the occurrence of the ultrasound signals on one another (Fig. 7.).

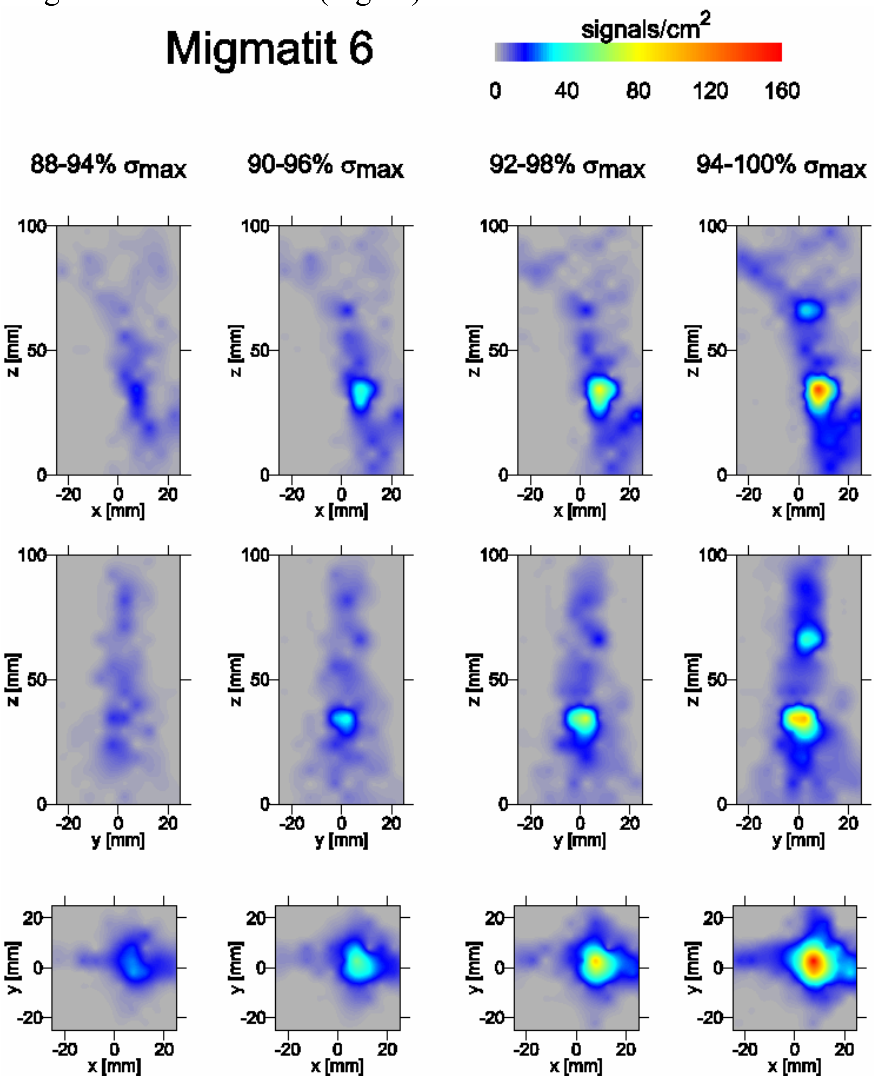


Fig. 7. Distribution of foci of occurrence of the ultrasound emission (events/cm$^2$), migmatit 6, evolution of foci in various loading intervals.

The laboratory experiments, carried out under various loading rates on granite and migmatite samples, disclosed that:

The loading rate affects the distribution of foci within the sample. It was found that under the highest loading rate (short-term tests) sources of ultrasound signals occur randomly throughout the volume of the rock sample, and their origins do not affect one another. This means that the rock reacts only to the action of the external force, and that no rheological processes are generated. In the medium-term tests, lasting 100 to 1000 minutes, however, the microfracturing are affected by the internal structure of the rocks and rheological processes. The ultrasound signals cluster only in particular parts of the rock sample, at surfaces of future total failure;

The level of loading (expressed in percent of the ultimate strength) in medium- and long-term tests is manifest as follows:
Under a pressure in excess of 95% of the ultimate strength the origins of the ultrasound signals affect one another, which was tested by the method of cross-correlation. This is associated with the redistribution of internal stress. The future surfaces of total sample failure could be predicted using this result in connection with the clustering of foci in limited parts of the rock sample;

Cross-correlation analysis enabled locations of increased concentrations of foci to be identified, how they were affected by the external acting force, as well as by the process of deformation of the whole sample. Even before total failure, the most endangered parts of rock samples, i.e. the nucleation centres of the future failure, can be determined in this way. This result is important also for extrapolating pulse time sequences (Vilhelm et al., 2003);

The method of cross-correlation used was found to be convenient in assessing how the occurrences of ultrasound signals affected one another. This is especially important in assessing the stability of underground structures (e.g., tunnels, underground storages, underground waste deposits, etc.) because it enables the most stressed parts of the rock massif to be assessed. This method can also be applied in monitoring the loading of bridge structures, dams, etc., especially if the load is close to critical state.

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