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Statistical study of acoustic emissions generated during the controlled deformation of migmatite specimens

J. Vilhelm[a,*], V. Rudajev[b], A.V. Ponomarev[c], V.B. Smirnov[d], T. Lokajíček[e]

[a] Charles University, Faculty of Science, Czech Republic
[b] Emeritus scientist of Czech Academy of Sciences, Czech Republic
[c] Schmidt United Institute of Physics of the Earth, Russian Academy of Sciences, Russia
[d] Physical Faculty, Moscow State University, Russia
[e] Institute of Geology of the CAS, v.v.i., Czech Republic

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ABSTRACT

Acoustic emissions generated during the mechanical loading of rocks provide information about the process of their fracturing and therefore have been used in the research of rock fracturing for many years. Laboratory loading experiments are used as a model of seismic processes in the field. Continuous loading is typically used to model natural tectonic processes, whereas stepwise loading can represent local stress field changes and evolution, similar to some features of rock fracturing due to water injection in the borehole with step-like injection history. During continuously increasing loading, acoustic impulses of a swarm character are generated. During stepped stress, however, the emission of acoustic signals generated has the character of an aftershock series and can be described by Omori's law for aftershock decay.

The present work focuses on a detailed analysis of the seismoacoustic emissions generated in rock specimen during the stepwise increasing deformation during laboratory loading tests. A cylindrical specimen of migmatite was subjected to cyclical and stepwise loading with controlled deformation. The stepwise deformation increase was approximately 0.8 mStrain per one step and deformation rate was cca 8 mStrain/s. This sudden increase of deformation was accompanied by peak stress increase with duration of approximately 2 s. During load testing, seismoacoustic emissions were monitored and time series of acoustic impulses were recorded. It was found that the higher the level of stress, the longer the duration of aftershock sequence. Analysis of the autocorrelation functions of individual sequences showed significant changes in parameters at maximum specimen stress. An increase was found in the values of first autocorrelation coefficients, which can be used to assess the stability of the rock specimen.

1. Introduction

Acoustic emissions generated during the mechanical loading of rocks provide information about the course of their disruption and therefore have been the subject of research for many decades[1–5]. Analysis of acoustic emission and elastic wave propagation velocity and its anisotropy in the rock samples can be used for many applications in oil, gas and geothermal energy industry, e.g. for determining in situ stresses from drill cores[6–8]. Known scaling similarities[9–11] allow extrapolating of laboratory results to field conditions what enables modelling of seismic processes by loading of rock samples. One of the greatest challenges when analyzing acoustic emissions is to evaluate changes in emission parameters depending on the level of stress so that eventual precursors of future total disruption of the rock can be found[12–16]. These studies analyze acoustic emissions generated from continuous stress applied to rock specimens. The work of Smirnov et al.[17] gives a detailed analysis of the acoustic emissions generated from both continuous and stepwise increase of uniaxial deformation. It was determined that during the continuously increasing deformation, acoustic impulses of a swarm character were generated. During stepped stress however, the sequence of acoustic signals generated has the character of an aftershock series and can be described by Omori's law for aftershock decay[11,12,18–21]. The parameters of this time distribution depend on the level of stress. It was found that the higher the level of stress, the longer the duration of aftershock sequence. The present work focuses on a detailed analysis of the seismoacoustic emissions generated during a stepwise increase in rock specimen deformation. Stepped stress generates acoustic emissions that have the character of aftershock sequences and conform to Omori's

* Corresponding author.
E-mail address: jan.vilhelm@natur.cuni.cz (J. Vilhelm).

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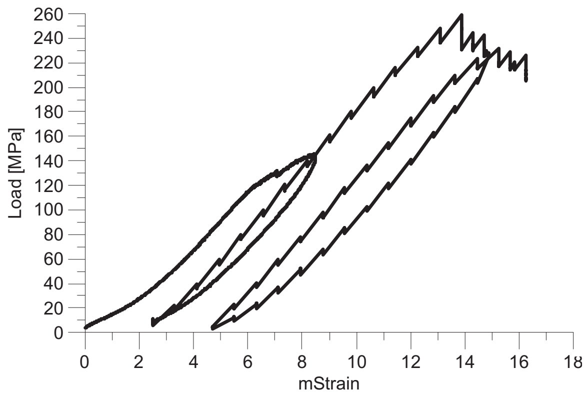

Fig. 1. Stress–strain diagram of three loading cycles on a migmatite specimen.

law for aftershock decay. Our research made it possible to monitor changes in the parameters of the aftershock sequence with respect to increasing levels of stress. Analysis of the autocorrelation functions of individual sequences showed significant changes in parameters at maximum specimen stress. An increase was found in the values of first autocorrelation coefficients, which can be used to assess the stability of the rock specimen.

2. Experiment

Measurements on specimens of migmatite were conducted at the Borok Geophysical Observatory, a facility of the Institute of Earth Physics of the Russian Academy of Sciences. The instruments and equipment used are described in detail in the work of 17,22. Cylindrical specimens of migmatite with a base diameter of 30 mm and height of 60 mm were subjected to cyclical stress with controlled deformation – a total of three cycles were carried out. Fig. 1 is a stress-strain diagram showing the loading of the migmatite specimen.

In the first cycle, when deformation was increased continuously, the specimen was subjected to a confining pressure of 5 MPa. In the next two cycles with stepped loads that confining pressure was increased to 30 MPa. The lower value of the confining pressure during the first loading cycle enables to achieve some degree of rock fracturing, while the higher level of the confining pressure in the second and third loading cycles resulted in increasing of the specimen strength in these two cycles. The chosen values of confining pressure were established experimentally on the same material with the goal to set up such conditions (specimen fracturing and stress conditions) to get reasonably high number of acoustic emission events during the stepped loading.

Fig. 2 shows the course of time of the experiment. The horizontal axis shows time in seconds while the vertical axis on the left shows load [MPa] and strain [mStrain]. The vertical axis on the right gives the number of impulses generated per second (acoustic rate).

In the first cycle, deformation was increased continuously up to load level corresponding to expected 50% of the migmatite rock strength under 5 MPa confining pressure. The actual maximum load in this cycle (145 MPa) reached 62% of the maximum load capacity of the specimen (achieved in the third loading cycle under 30 MPa confining pressure). Continuously increasing deformation generated acoustic emissions of a swarm character[17].

In the second cycle, we applied step-like axial loading under confining pressure. The deformation was abruptly increased and held constant afterward. Each loading step generates a sequence of acoustic events similar to an aftershock sequence[23]. The duration between consecutively following abrupt increases in deformation was approx. 7 min. This deformation increase was approximately 0.8 mStrain and deformation rate was approx. 8 mStrain/s. The sudden increase of deformation was accompanied by peak load increase with max. duration of 2 s.

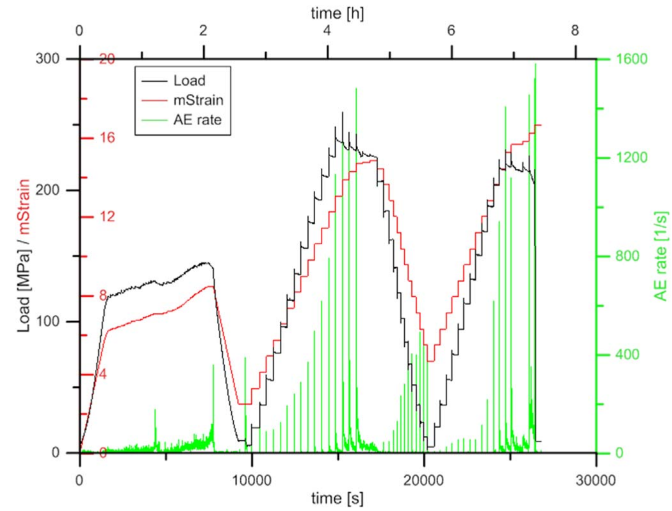

Fig. 2. Overall loading time pattern.

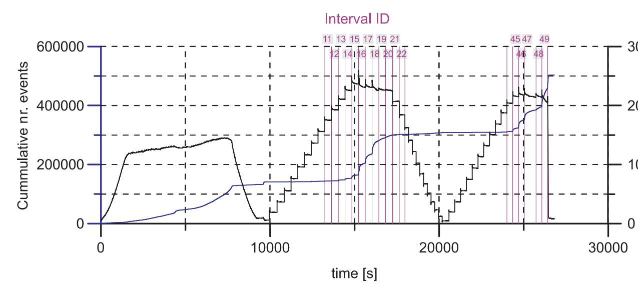

Fig. 3. Designation of intervals for which aftershock sequence analysis was performed.

A significant increase in acoustic emissions was not observed until reaching an axial load of approx. 175 MPa at the interval given in Fig. 3 as Series 11. The maximum load of the specimen after peak load subsided was at interval 15 (240 MPa) – see Fig. 3. At interval 16, and when increasing deformation by the same amount (0.8 mStrain), load only reached 238 MPa. At following intervals 17–20 deformation was increased by 0.4 mStrain (intervals 17 and 18) and 0.08 mStrain (intervals 19 and 20). Even when increasing deformation there was a gradual decrease in load, so that at interval 20 load was 230 MPa. Constant confining pressure (30 MPa) prevents disrupting of the specimen. Beginning with interval 21 specimen deformation was stepped down in controlled fashion, resulting in stepped drops of stress (at interval 21 by 22 MPa and at interval 22 by 24 MPa).

The third loading cycle essentially reproduced the course of the second cycle. At all intervals, with the exception of interval 47, constant deformation was maintained for a period of 7 min. The duration of constant deformation at interval 47 was double, i.e. 14 min. This occurred due to the technical conditions of the experiment. After achieving a pressure of 220 MPa (intervals 46–48) and maintaining constant deformation at interval 49, there was a significant drop in stress and then sudden disruption of the migmatite specimen.

During load testing, seismoacoustic emissions were recorded using a single-channel seismoacoustic apparatus. Seismoacoustic impulses were registered using a piezoelectric sensor with a resonance frequency of 290 kHz that was placed on the bottom jaw of the press. Recording was continuous, enabling the identification of 2400 impulses per second. Automatic detection was set with threshold criteria, i.e. the maximum impulse amplitude had to exceed a pre-set value[17].

The acoustic emissions generated during stepped increase of deformation (2nd and 3rd cycles) had the character of aftershock sequences that could be described by Omori's law for aftershock decay. To assess the stability of the loaded rock specimen, these aftershock