Scaling in Fracture: From Rocks to Earthquake Physics

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Abstract: We introduce a statistical analysis of time series extracted from rock fracture experiments to earthquake catalogues in order to demonstrate common features underling in these processes. We demonstrate that in all considered cases a frequency-energy distribution similar with the well known in seismology Gutemberg-Richter law appears along with a waiting time distribution which can be described by a unique scaling function. The resulting scaling functions common in laboratory rock fracture effects, earthquakes and acoustic emmissions suggest a general validity for fracture processes.

Key-Words: Rock Physics, fracture, Earthquake Physics

1 Introduction

Despite the large amount of experimental data and the considerable efforts undertaken [1], many questions about fracture have not yet been answered. The fracture phenomena, particularly those concerning inhomogeneous materials, in association with earthquake physics attract the interest of the scientific community since will support the selection of earthquake physics models and the understanding of possible earthquake precursors [2,3,4]. To this direction most of the possible precursors are related to the material deformation and one of the most promising one, the electric one, could be associated with crack generation [5-11].

In order to understand the underlying physics that produce these electric signals, a number of laboratory experiments of mechanical stress up to sample fracture have been conducted on minerals and rocks (dry and saturated) [12-18]. These experiments have been combined with numerous studies and recordings of acoustic emissions due to mechanical stress cause microcracking in rocks [19].

The laboratory studies on emitted electric signals from rock specimens at the time of fracture, suggests a variety of mechanisms that these signals are produced. Among the reported mechanisms piezoelectric effect of quartz [20], electrokinetic effect due to water movement [21], point defects [22], emission of electrons [23]; and moving charged dislocations [5, 7-10, 11] are incuded.

Recently in a series of laboratory experiments conducted on calcite samples have confirmed that the application of a uniaxial stress is accompanied by the production of weak electric currents that have been described by the term Pressure Stimulated Currents (PSC) [9, 18,19, 24-29]. In particular, Pressure Stimulated Currents and acoustic emission (AE) due to microcrack growth precedes the macroscopic failure of rock samples under constant stress or constant stress rate loading [24-33].

In the present work we show that despite this difference the scaling law of frequency-size distribution and the probability density function (PDF) for the time interval between PSC events are similar with that observed in AE and seismicity. In particular, the PDF of pressure stimulated currents emitted during laboratory rock fracture experiments strongly suggest a universal character of the waiting time distribution and self-similarity over a wide range of activity in rock fracture.

Furthermore, since the AE due to microcrack growth follow simirar laws as PSC can be considered indicative that the moving charge dislocations (i.e., growthing microcracks) is the driving mechanism of PSCs as suggested in Refs. [7-11]. We analyse the PSC time series of laboratory rock fractures obtained from different compressed experiments in calcite.

2 Scaling laws: from fracture to earthquakes.

Calcite is a geomaterial of known physical and chemical properties, which have been thoroughly presented in the previous works [24-29,38,39]. Details on the experimental installation are given in [17,18,24-29]. Typical examples of time series recordings in calcite are given in Fig. 1.

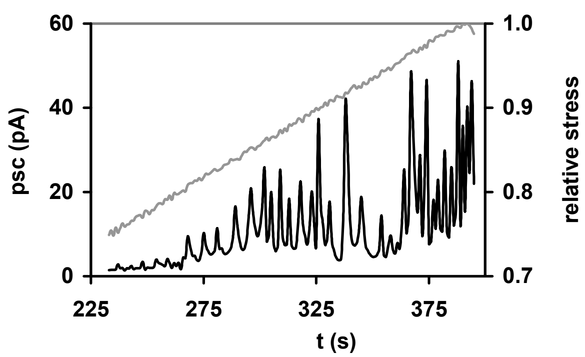

Figure 1. PSC recordings in calcite samples. The straight line is inticates the relative or normalized applied stress.

In the following, we focus on two quantities to characterize each PSC event a) the time of occurrence and b) the square of PSC adjusted amplitude I_{psc} since it is express an energy quantity (i.e., $\varepsilon_i = I^2_{psc(i)}$). Fig. 2 shows, the commulative frequency –size distribution of ε. Typical examples of time series recordings in calcite are given in Fig. 2. Details on the samples calcite and experimental conditions the PSC technique summarized in Table 1.

The function $P(\varepsilon_i > \varepsilon)$, is rather similar to the Gutenberg-Richter law, supporting a power-law –like decrease, with exponent b always close to 1.0, which characterizes the frequency-magnitude relation of earthquakes and AE [35-37].

Table.1. Calcite samples and experimental conditions

Sample	Stress rate (kPa/s)	Failure stress (MPa)
Calcite (445-11)	3.3	53.44
Calcite (445-04)	32	54.84
Calcite (556-03)	94	59.4
Calcite (445-07)	72	44.64

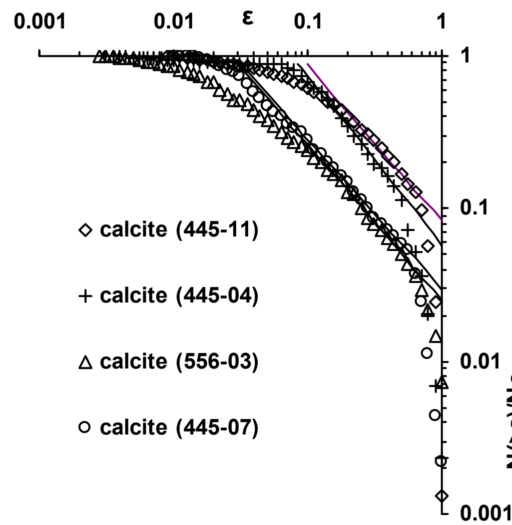

Figure 2. The commulative frequency–size distribution of ε.

To analyse the recordings in PSC and earthquake series, we transforme them into a point process where events occur at times t_i with $1 \le i \le N$, and therefore, the time between successive events can be obtained as $\tau_i = t_{i+1} - t_i$. These are the waiting times which are also referred to as recurrence or interevent times. The associated commulative PDF is denoted by $P(\tau)=P(\tau_i>\tau)$. Then in order to present the PDF in a unique way the normalized waiting times $\chi = \tau / <\tau>$ where $<\tau>=(t_N-t_1)/(N-1)$ is the respective mean waiting time are analysed for calcite rocks fracture experiments and earthquakes as well.

Pressure Stimulated Currents, acoustic emissions and earthquake data appears in different time and special scaling and display considerable differences. In Ref. [34] it was shown that the PDF of earthquake waiting times -without distinguishing between foreshocks, main shocks, or aftershocks- for different spatial areas, time windows and magnitude ranges can be described by a unique distribution if time is rescaled with the mean rate of seismic occurrence. It was shown, in particular, that the distribution holds from worldwide to local scales, for quite different tectonic environments, and for all magnitude ranges considered. Fig. 3 represent reanalysed the waiting time distribution in Californian earthquakes. On the other hand, in [35-37] was presented that the temporal, spatial and size distribution of AE events follow a power–law just as it commonly observed in earthquakes.

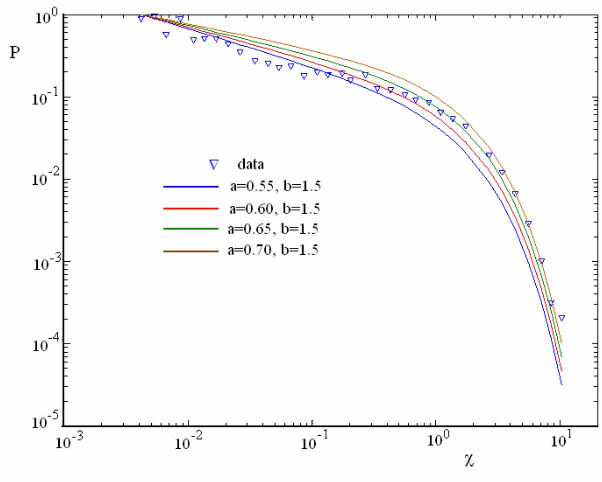

Figure 3 Distribution of interevent times in Californian earthquakes.

In figure 4 we present the P(χ) in the case of PSC. The excellent data collapse implies that P(χ) does not depend on the particular rock fracture experiment and for a given fracture experiment, the PDF P(χ) is determined by its mean waiting time <τ> and the universal scaling function P(χ) which can be well approximated by a gamma distribution

$$P(\chi) \propto \chi^{-(1-\gamma)} \exp(-\chi / B) \qquad (1)$$

with $\gamma \approx 0.8$ and $B \approx 0.7$. Therefore, we have essentially a decreasing power law with exponent about $1-\gamma = 0.2$, up to the largest values of the argument, χ (close to 0.5), where the exponential factor comes into play. The latter expression indicates a strong similarity with that observed for AE and earthquake data [30, 35-37] (see figure 3).

Taking into account that PSC, AE and earthquake observations follow the same law, it is strongly supported the idea that P(χ) given in Eq. (1) is possibly a universal result for rock fracture. It further implies that P(χ) is self-similar over a wide range of activity rates spanning at least 3 to 4 orders of magnitude for the experiments considered here.

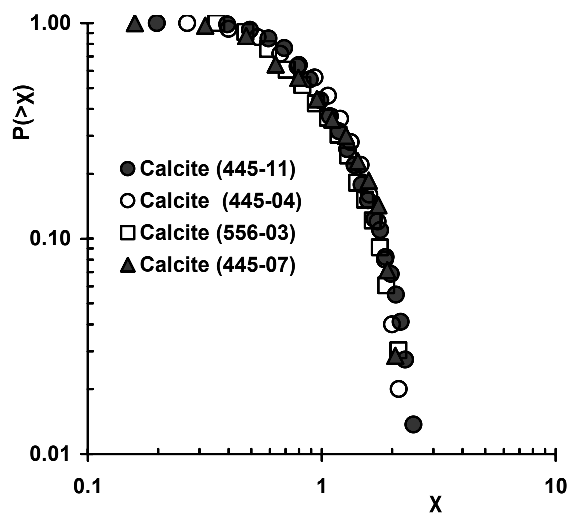

Figure 4. The probability density function of the normalized PSC waiting times $\chi = \tau / < \tau >$ for calcite rocks fracture experiments.

3. Concluding Remarks

To summarize, we have shown that Pressure Stimulated Currents obey a frequency –sixe law similar with the well know Guteberg –Richter law with a b-value close to one. The probability density function for PSC waiting times in laboratory rock fracture is self-similar and can be de scribed by a unique and universal scaling function P(χ). Its particular form can be well approximated by a gamma function implying a broad distribution of waiting times. This is very different from an exponential distribution expected for simple random Poisson processes and indicates the existence of a nontrivial universal mechanism in the PSC generation process. All the aforementioned similarities with AE and seismicity and the form of the power laws even suggests a connection with fracture phenomena at much larger scales impling that a basic general mechanism is "actively hidden" behind all this phenomena..

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