

Gutenberg-Richter-type relation for laboratory fracture-induced electromagnetic radiation

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The fractal nature of electromagnetic radiation induced by uniaxial and triaxial rock fracture is considered. Both the well-known Gutenberg-Richter-type and the Benioff strain-release relationship, for earthquakes and starquakes, are shown to extend to the microscale (millimeters-centimeters). Results show that both the b value of the Gutenberg-Richter-type law and the slope of the Benioff strain-release relationship of the electromagnetic radiation signals are similar to values known for earthquakes. These results imply that a common mechanism is acting at all scales.

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I. INTRODUCTION

A. Fractal nature of earthquake

A fundamental observation in seismology is the Gutenberg-Richter law [1],

$$\log(N) = a - bM, \quad (1)$$

where M is the earthquake magnitude (which is defined as the logarithm of the integral of slip along the fault during an earthquake), N is the number of earthquakes having magnitudes greater than M , and a and b are constants. This power-law or fractal distribution is valid both for main events and for aftershocks [2]. It is presently thought that such a distribution may be a fundamental result of “multiple fracturing” [3], when spontaneously occurring microcracks tend to coalesce leading, by numerous upscalings, to a catastrophic failure. A similar relation is also observed in laboratory studies of acoustic emission [4,5]. It is even true for energy distribution of neutron starquakes [6] (the source of a starquake is a fracture in its neutron crust, which may release strain energies of up to 10^{46} erg [7]), which is many orders of magnitude larger than that of an earthquake.

Recently, enough data has been collected to extract statistics on individual systems of earthquake faults [8], and it was found that the distribution of earthquake magnitudes may vary substantially from one fault system to another, and for different Earth regions.

Regarding the exponent “ b ” of the power-law distribution, it was previously claimed to be universal and close to one [1]. In Ref. [9], the related b values (for many earthquakes in Italy calculated for the period 1900–1993) are in the range 0.7–1.35. Elgazzar [10] estimated the b value to be 0.85 ± 0.2 . Nanjo, Nagahawa, and Satomura [2] give b to be between 0.5 and 1.5. It has recently been claimed that “ b ” fluctuates in time, and depends on the earthquake magnitude [11–13].

In recent years, numerous investigators tried to explain b

theoretically. For example, “self-organized criticality” models were proposed [11,14–16] to explain this scaling law as being a result of the extremal nature of the dynamic rules governing the system. There are also other deterministic models [13,17] describing earthquake dynamics by the friction and elastic forces acting in the fault zone. For example, the one-dimensional Burridge-Knopoff model [18] leads to the Gutenberg-Richter law with $b \approx 1$.

Anton [19] proposed an analytic model based on a relation between stress-release rate and kinetic-energy loss by seismic waves, and noted that the relation $b < 1$ implied that the stress-release rate was greater than the loss of kinetic energy by seismic waves.

Gabrielov *et al.* [20,21] developed a “colliding cascades model” consisting of a hierarchical structure. They proposed that an external load applied to the largest block is transferred hierarchically to the smallest components. Fracture processes expand in an inverse manner. The two processes “collide” and interact. On the basis of this model, they argued that the b value should be 0.53 for main earthquakes and 0.69 for aftershocks.

B. Electromagnetic radiation (EMR) before earthquake

During the 1970s and 1980s, interest in EMR increased in connection with the problem of earthquake (EQ) prognosis. Numerous investigations measured EMR anomalies prior to earthquakes and to volcanic eruptions [22–26]. It was assumed [24,27–30] that the anomalies of EMR prior to EQ were due to a deformation of the Earth’s surface, which resulted in the formation of microfractures and in friction of the nearby rock blocks. Each of these processes could lead to EMR generation. This abnormally high EMR amplitude occurs hours or even days before an EQ and decreases at the same moment when the EQ takes place [31].

Parrot *et al.* [32], after a detailed consideration of a large number of presently known EMR-EQ investigations, remarked that although the existence of EMR in relation to seismic and/or volcanic activities was clear; EMR selection out of a host of artificial signals (industrial noise, etc.) remained a significant problem. Nevertheless, investigations of

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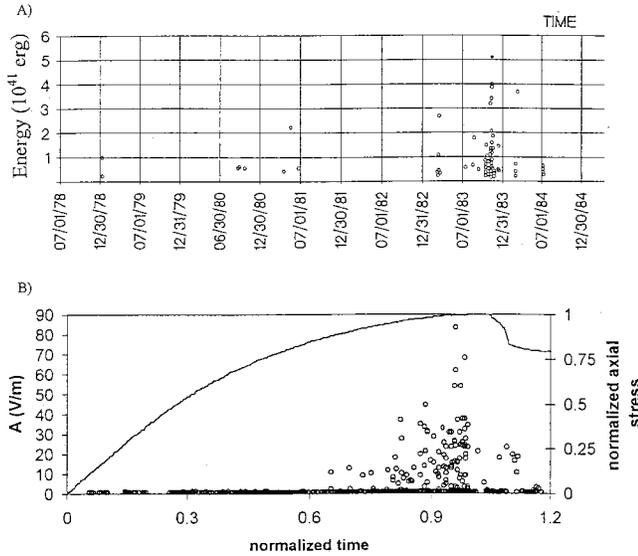


FIG. 1. A qualitative comparison between energy changes during starquakes (a, after [6]) and amplitude changes of electromagnetic radiation induced by rock compression.

EMR as a precursor to EQ continue [33–36] and presently, there is an agreement in the literature that EMR might be a prospective forecaster for EQ’s [37–39]. Rikitake [40] analyzing 60 EQ events measured in Japan showed that EMR is a “short-term” precursor, the mean time of which is estimated to be six hours. However, in contrast to acoustic emission, there exist no measurements of the fractal behavior of these EMR signals.

Amplitude changes of fractures during laboratory compression tests of brittle materials were considered by Lockner *et al.* [4,5] to be similar to those occurring in EQ. This kind of similarity may also be gleaned from a comparison between energy release during starquakes [Fig. 1(a) [6]] and our measurements of amplitude of electromagnetic radiation induced by chalk compression failure [Fig. 1(b)]. In this paper, this similarity is investigated, focusing on the possibility of a power law for EMR induced during conventional uniaxial and triaxial fracture of chalk samples.

II. EXPERIMENT

A. Equipment and method

The experimental setup is described in detail in Refs. [41–43]. It consists of a “stiff” press [44], an antenna system, and the related electronics. Uniaxial and triaxial compression tests were performed. Samples of chalk were cut from blocks, with unified co-orientation, into standard cylinders of 100 mm in length and 53 mm in diameter. The ends of the samples were scrupulously polished to get homogeneity of the stress field under compression. Each sample was tested by an axial strain rate of $1 \times 10^{-5} \text{ s}^{-1}$ and, laterally, by a different hydrostatic oil pressure.

B. Material

Our chalk samples were drilled from Middle Eocene layers along Wadi Naim in the Beer Sheva syncline [45]. The

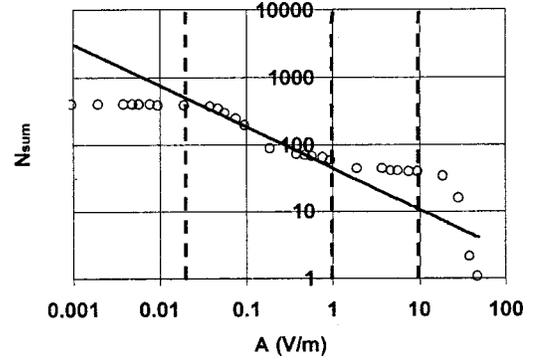


FIG. 2. The cumulative number (the number of signals having amplitudes larger than) of EMR signals (measured additively from 24 chalk samples during uniaxial and triaxial conventional tests) vs EMR pulse amplitude.

density of all investigated samples was $2.16 \pm 0.01 \times 10^3 \text{ kg/m}^3$. The strength of chalk under compression may vary considerably, from values of around 1 MPa when wet to some 50 MPa when extremely dry. Therefore, we applied a strict drying process to our samples, which involved a cycle of heating to 110°C in 24 hours, and then immediately removing to a desiccator, in order to avoid any water absorption by the samples. The maximal axial loads used in the experiments varied from 30–60 MPa, and the confining pressures from 0–5 MPa. Properties of the investigated chalk samples were shown in detail in two of our papers [46,47].

III. RESULTS AND DISCUSSION

Figure 2 shows the cumulative number (the number of signals having amplitudes larger than) of EMR signals (measured additively from 24 chalk samples during uniaxial and triaxial conventional tests) vs EMR pulse amplitude.

Since the voltage output of the EMR pulses “ \bar{A} ” depends on the antenna reaction (antenna efficiency), which changes with frequency, it was compensated as $A = f(\bar{A})$ (A being the field amplitude reaching the antenna), by the appropriate antenna efficiency chart (EHFP-30 Near Field Probe set, Electro-Metrics Penril corporation). We were thus able to compare heights of EMR signals with different frequencies.

EMR pulse amplitudes changed by five orders of magnitude (Fig. 2), from 0.001–100 V/m. The figure consists of four parts. Its main part is consistent with a Gutenberg-Richter-type law with a b value of 0.62 ($R^2 = 0.95$).

$$N_{\text{sum}} = 51.44A^{-0.62}. \quad (2)$$

Note that this b value is close to $2/3$. On both ends of the graph, there is a deviation from the Gutenberg-Richter-type law. The b value for the small amplitude range is very low (0.02, $R^2 = 0.76$). This small value might be related to either an incomplete sampling of small events or to noise or to a physical effect governing the process. In the range of large amplitudes $1 < A < 10$ V/m (Fig. 2), the b value is also significantly lower (0.08, $R^2 = 0.76$) than in the main part, which might possibly be due to the finite size of the sample. Note that the EMR amplitude in the range of $1 < A$

<10 V/m is measured when the external stress is higher than the sample's elastic limit [Fig. 1(b)]. Figure 2 has also a fourth part ($A > 10$ V/m) with $b = 2.3$ ($R^2 = 0.77$). This is the range immediately before sample collapse [Fig. 1(b)].

Several investigators have noted this slope-change effect for seismic data as values in the smallest and largest ranges deviated from the Gutenberg-Richter-type law. For example, Lockner [4,5] showed a rolloff in the distribution of acoustic emission signals at low amplitudes and explained it by the incomplete sampling of small events [4,5]. Kossobokov, Keilis-Borok, and Cheng [6] noted this slope-change effect in the high range of earthquakes and explained it as being due to the maximum energy release being limited by the size of the crust and by the energy density. They also noted that for the largest earthquakes, the downward slope may altogether disappear or even turn into an upward slope.

A slope-change effect was also observed by Molchan, Kronrod, and Panze [9] for induced seismicity both in the range of small and of large earthquakes.

The decrease of the b value with stress, as happens here between 1 and 10 V/m (Fig. 2), is also a known effect (e.g. [4,5]).

Our results for EMR amplitudes in compression agree with those of Refs. [2, 6, 10, 19–21] for the distribution of EQ magnitudes in that the b value is of the order of 2/3.

Note that Fig. 1 exhibits the escalation of the fracture process before collapse. Figure 1(a) [6] shows the energy of starquakes vs time, which occurred at the distance of about 40 000 light years from earth. Figure 1(b) gives a normalized EMR amplitude-stress-time graph of all chalk samples. Stress values [Fig. 1(b)] were normalized by the peak stress value. Comparison shows that the two graphs are very similar.

Fracturing processes may be measured either by intensity changes (see, e.g., Fig. 2) or by their energy release. The latter is usually represented by the so-called “cumulative Benioff strain release” [6,20,21,48], which relates the total sum of the square root of the energy released for sequential fracture events to the time prior to the collapse failure. Hence, in addition to the Gutenberg-Richter purely statistical law, the “cumulative Benioff strain-release” relation enables us to monitor the continuous development of the upscaling fracture process through time.

The measured EMR amplitude is proportional to the magnetic field intensity (H) reaching the antenna. Since the en-

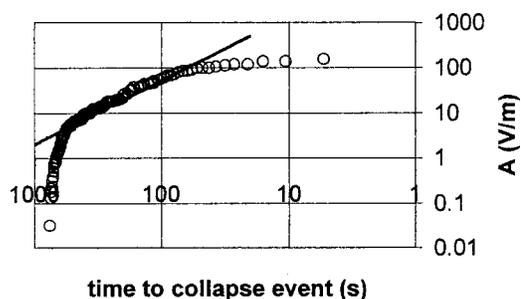


FIG. 3. The “Benioff strain-release” relationship of a cumulative amplitude of all EMR signals registered during all samples’ compression vs time before their collapse failure (time goes backwards from the moment of collapse).

ergy of the electromagnetic field is proportional (Pointing vector) to $|H|^2$, the EMR amplitude is proportional to the square root of the energy. Figure 3 shows a bilogarithmic graph of a cumulative amplitude of all EMR signals registered during all samples’ compression vs time before their collapse failure. Since maximal values of EMR amplitude are excited by the samples’ collapse failure, their occurrence times were taken as the zero time for each sample.

The graph (Fig. 3) shows an almost constant slope in its middle part (about a whole decade). It was fit to a power law ($R^2 = 0.987$ and $1 + \alpha = 1.42$) and is seen to be accompanied by some logarithmic-periodic variations. This graph is very similar to the usual “Benioff strain-release” ones (e.g., [6]) and the slope of its main part is close to $1 + \alpha = 1.35$ of Ref. [49].

Results obtained in this paper show that both the b value of the Gutenberg-Richter-type law and the slope of the Benioff strain-release relationship of electromagnetic radiation signals obtained during chalk fracture in the laboratory are similar to those measured in earthquakes. Both the qualitative similarities and a fortiori the almost exact power laws are striking. The fractal nature of the processes controlling earthquakes and starquakes may therefore be extended to a microscale regime. This “global” nature of multiple fracture effects evidently implies that a basic general process is “acting behind” all these phenomena.

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