Observation of significant differences between electromagnetic and acoustic emissions during fracture processes: A study on rocks under compression loading

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Abstract. Electromagnetic radiation (known as electromagnetic emissions) related to processes of loading and fracture in different types of materials (from metals to rocks) has been widely reported. The physical mechanisms behind these emissions are still under discussion, however, it is commonly accepted that they are created by some of the micro-cracks that appear in the sample during fracture processes. Nucleation and growing of micro-cracks generate mechanical waves (acoustic emissions), therefore, each electromagnetic emission should be linked with some acoustic event. Furthermore, it is expected that the electromagnetic and acoustic activities (number of emissions per second) have the same general characteristics. Contrary to what is usually reported, we find that there are significant differences between acoustic and electromagnetic emissions in loading processes on rocks. These differences were detected during the compression of a typical laboratory-scale sample of granite when it is compressed at a rate of around 20 kPa/s. We found two important discrepancies: i) There were at least 20 electromagnetic bursts (out of around 200) that were not coincident with any acoustic event. ii) The electromagnetic activity in general shows its maximum value when acoustic activity is very low. Both emissions just coincide at the moment of the final collapse. These results strongly suggest the existence of a non-fracture mechanism related to the origin of electromagnetic emissions. This could have important consequences for the field of non-destructive assessment of materials and even in the study of earthquake precursors and forecasting.

1. Introduction

In brittle and disordered materials, fracture processes are dominated by the coalescence of micro-cracks that appear gradually and randomly at different points of the sample. The presence of micro-cracks releases elastic energy in the form of mechanical waves, this is known as acoustic emission (AE). Simultaneously, micro-crack development is followed by electric charge separation processes. Charge recombination through the conductive rock generates electric currents and the consecuent electromagnetic fields, this is known as electromagnetic emission (EME).

The study of AE and EME has been proposed as a way to follow the fracture process in a wide variety of problems, such as monitoring the health structures of reinforced concrete [1–4], early

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warning systems in mine constructions [5] or even forecasting big earthquakes [6]. While it is clear that AE are caused by a stress relaxation mechanism, there is no agreement about the physical mechanism behind EME. For example, Tzanis, *et al.* [7] have proposed the movement of charged dislocations in rocks as generator of electromagnetic fields. Gershenzon, *et al.* [9] suggested a symmetry breaking process between positive and negative charges induced by the micro-cracks movement. Gernets, *et al.* [8] associated EME to the piezoelectric properties of some materials. Finally, Rabinovitch, *et al.* [10] explained some characteristics of EME waveform assuming that electromagnetic fields are created by oscillating electric dipoles coupled with phonons on the surfaces of micro-cracks.

Besides the differences between these mechanisms, it is clear that they all link EME with some aspects of micro-cracks and therefore, the source of the EME must be a fracture mechanism. Experimentally, this implies that every electromagnetic event must be detected simultaneously with at least one AE.

In this paper we show, based on data from a compression loading experiment performed on rocks, that there are important differences between AE and EME. These differences are detected by comparing single events and also by a statistical analysis. It is established that the occurrence of an EME is not directly related to an AE. This is then discussed in the context of fracture precursors. We also use energy-duration maps for AE and EME to show that, statistically, the EME are not correlated with all the acoustic activity but with events originating from lower speed fracture propagation.

2. Experimental set-up

The sample used for this experiment was a cylindrical core of granite (diameter ≈3 cm, height ≈6 cm). Mineralogical analysis showed that the rock is composed by: quartz 30%, plagioclase 30%, feldspar 15%, biotite 15% and hornblende 8%. The rock was compressed at a rate of ≈20 kPa/s by a universal testing machine. A piezoelectric acoustic sensor was located at the base of the machine to detect the acoustic signal. The electromagnetic signal was acquired by a capacitive sensor made of two thin copper sheets (≈ 5 cm × 5 cm) located 5 mm from the rock's surfaces. The entire experimental set-up was put inside a Faraday cage to avoid electromagnetic interference. Both signals were pre-amplified by a factor of 100, band filtered and the data were acquired at a rate of 2.0 MHz. In order to identify single events (both EME and AE), the noise threshold was set at 26 dB. This choice is common in this kind of experimental setup [11]. An acoustic event starts at the time t_i when the acoustic signal $V(t)$ crosses the threshold and finish at the time t_f when the signal remains below the threshold for at least 1000 μs. An identical procedure was used to identify single electromagnetic events. Evidently, the duration was defined by $\tau = t_f - t_i$. The energy of the single events was computed as the integral of $V^2(t)$ for the duration of the emission and all values were normalized to the maximum energy E_{max}. Two examples of single acoustic and electromagnetic events are shown in Figure 1 and Figure 2.

3. Results and discussion

During the experiment we found several key differences between both emissions. First, the waveform of the AE shows the typical form associated with lab-quakes, with a duration time going from 100 μs up to 5000 μs. The EME, on the other hand, has the characteristic curve for an electric discharge process in an RC circuit (see Figure 1 and Figure 2). This points to the fact that a charge separation process occurs in a very short period (less than a microsecond) and the posterior recombination of electric charges, with a duration of about 100 μs, occurs through the conductive rock. Although several authors have found close similarities between the waveforms of the AE and EME, our data clearly do not show that closeness. Even more, we detect multiple EME coincident with just a single AE (Figure 3). The difference can be explained, probably, by the difference in content of piezoelectric materials or the humidity inside the rock due to different drying processes.

A more important difference between AE and EME comes from the existence of large and intensive chains of AE events with no evidence of significant electromagnetic activity. Figure 4 compares the times series for AE during high activity with the same time intervals for EME. Clearly, the electromagnetic signal does not show the presence of any emission above the threshold. This fact is not an exception but the rule: the number of detected AE is about 10000, while we were able to detect around 230 EME. therefore, most of the AE are not coincident with EME.

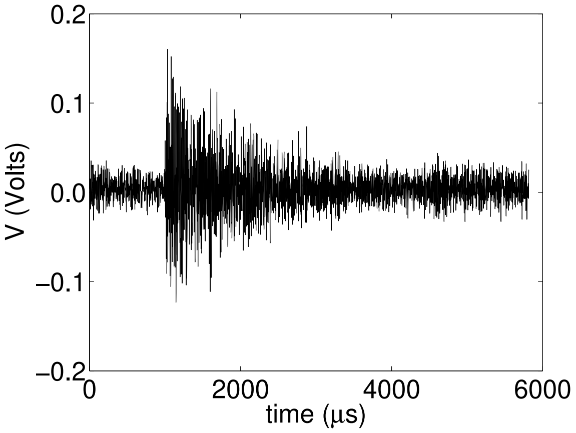

Figure 1. Typical waveform for a single acoustic event.

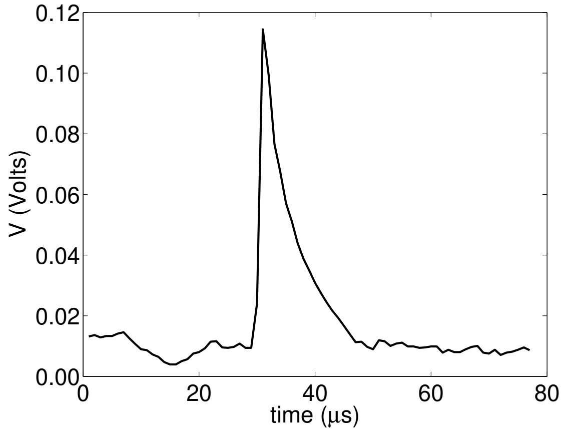

Figure 2. Typical waveform for a single electromagnetic event.

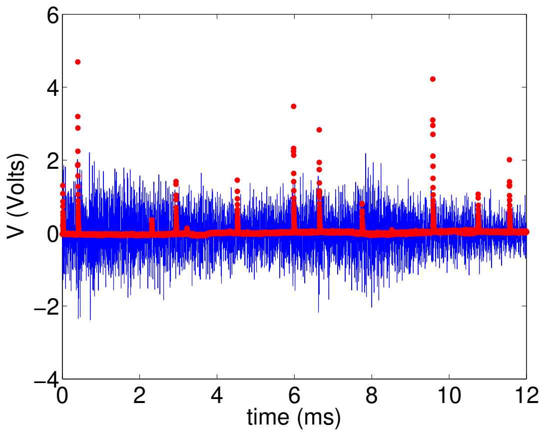

Figure 3. Multiple EME (red) occurring during the same τ of a single AE (blue).

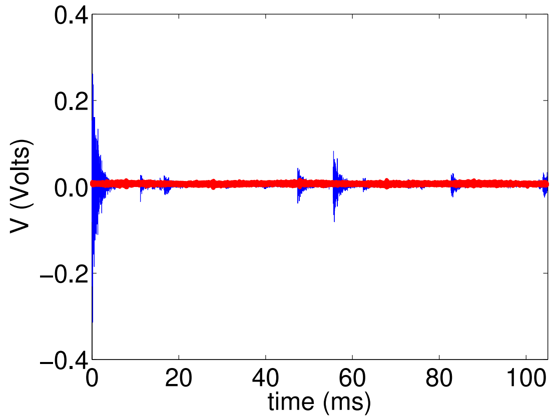

Figure 4. Presence of AE (blue) with no significant electromagnetic activity (red).

The most surprising result found during the experiment was the existence of EME during periods of insignificant acoustic activity. Figure 5 shows an example of this phenomenon. According to all the models discussed in the Introduction, EME should be a direct consequence of the micro-cracking process and therefore shares a common origin with AE; in this framework every EME should be coincident with some AE. However, our results suggest that some EME originate from a non-fracture mechanism.

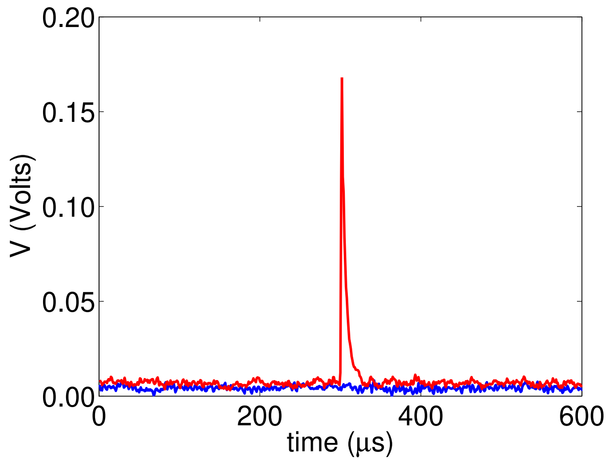

Figure 5. Electromagnetic emission (red) in a time window with no significant acoustic activity (blue).

The difference between acoustic and electromagnetic signals can be also seen from a statistical perspective. Figure 6 shows the acoustic activity (number of AE per second) superposed on the electromagnetic intensity, both as functions of time.

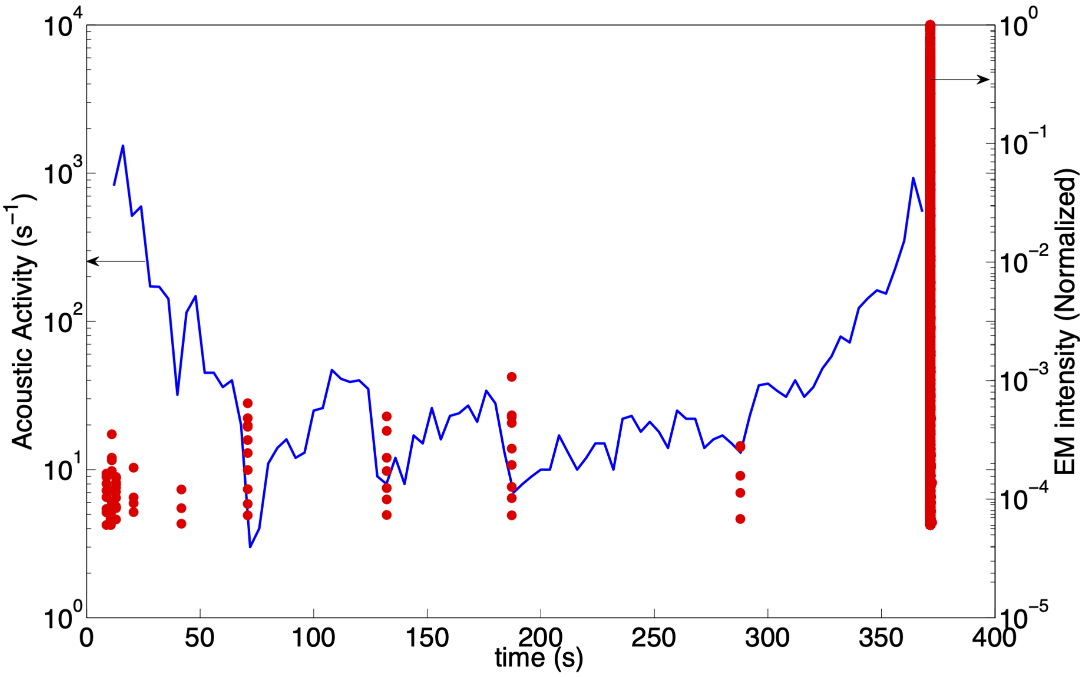

Figure 6. Acoustic activity (number of emissions per second, blue) and electromagnetic intensity (normalized, red) as a function of the running time.

Figure 6 shows that not only single AE and EME emissions have differences but so do the acoustic and electromagnetic signals in general. From this statistical perspective, both emissions are present with high intensity at the beginning and the end of the experiment. However, in the middle of the process, a high electromagnetic intensity coincides with a low acoustic activity. This confirms that most of the electromagnetic energy emitted from the rock does not come directly from micro-cracks.

Finally, to confirm that the origin of EME has a strong non-fracture component, we represent the emissions as an energy-duration map ($E-\tau$ map). $E-\tau$ maps have been used to characterize acoustic events during rupture processes on several materials. For example, Soto-Parra *et al.* [12] have found that collapsing and twinning events during the compression of porous Ti-Ni obey a law of the form $E \sim \tau^n$ where $n = 3$ for collapsing and $n = 1.5$ for twinning (and detwinning). $E - \tau$ maps also have been used in the study of reinforced concrete samples [1] and, in general, to validate several models of mean field theories for the dynamics of slip avalanches in slowly deformed solids [13].

Figure 7 presents the $E - \tau$ maps for the AE and EME. In general, it is possible to see that the number of AE ($\approx 10^4$) is much bigger than the number of EME ($< 10^3$). Even more, the duration for AE is up to 10^4 times bigger than the duration for EME. But the main difference between these two emissions is that the AE occupy a well defined region (band-like structure) between two straight lines (black lines) on a log-log scale, while the EME clearly do not show the same behavior. A direct inspection shows that the slope of the black lines is $n \approx 3$. According to theoretical models this is an indicator of fracture events [13]. Also, assuming that the micro-cracks propagate at a constant speed, the relation between E and τ can be expressed as $E \sim D^3$ where D is the length of the fracture. This hypothesis is similar to the well known magnitude—rupture area $(M - A)$ relation for earthquakes [14]. EME can not be fit into a power law relation and therefore there is no clear relation with fracture events. However, the $E-\tau$ map for AE is useful to get insight into the origins of the EME. Figure 8 shows, inside the red squares, the AE that contain at least one EME or are very close (less than a τ) to an EME. There is a clear tendency for EME to appear close to the AE on the lower part of the band, which corresponds to low speed fracture propagation events. This shows that, although there are important discrepancies between the acoustic and electromagnetic signals, electromagnetic events are correlated with some type of acoustic events.

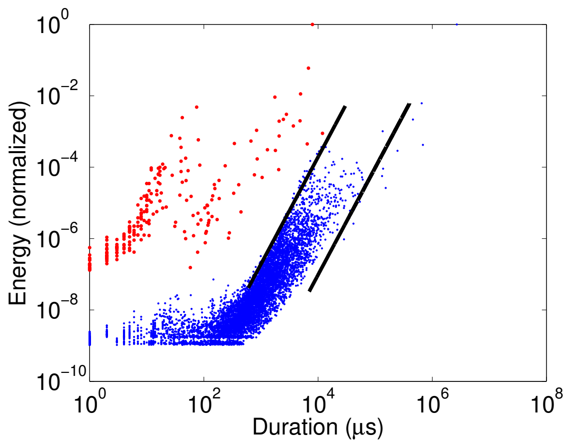

Figure 7. Energy–Duration $(E - \tau)$ maps for EME (red) and AE (blue). Energies are normalized to their maximum values. Straight black lines represent $E \sim \tau^3$.

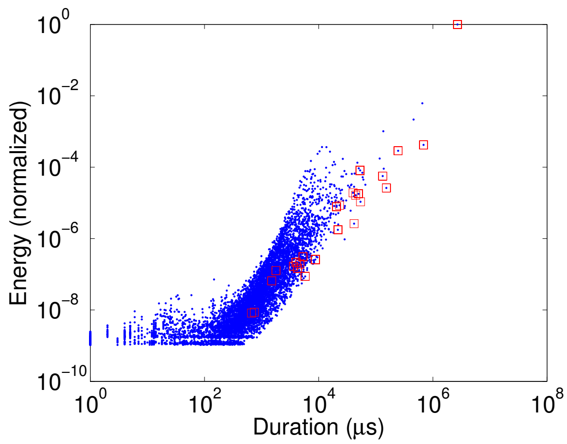

Figure 8. $E - \tau$ map for AE (blue). Inside red squares acoustic events that contain at least one EME or are very close (less than a τ) to an EME.

4. Perspectives

The possible non-fracture origin for EME is interesting because some electromagnetic events could be precursors of AE. This pre-fracture information would be useful in different contexts, especially in the field of earthquake forecasting where some striking results have recently been reported at the lab and field scales [15, 16]. Evidently, this hypothesis must be evaluated in experiments where EME can be located looking for spatial correlations with AE. Also, theoretical models of fractures should be extended to include, in some way, the electromagnetic component from an individual and statistical perspective. As far as we know, this kind of research has not yet been carried out and would be innovative in the field of fracture processes.

5. Conclusions

We carried out fracture experiments on a brittle material (rock) to see the relation between acoustic and electromagnetic emissions during a loading process. Contrary to the results obtained by several groups in similar investigations, we found clear differences between the acoustic and electromagnetic signals. These differences can be appreciated in both the single emissions and a statistical analysis. Long and intensive chains of acoustic events were detected with no significant electromagnetic activity above the noise threshold. Reciprocally, we were able to detect around 20 electromagnetic emissions (out of 200) which are not time-coincident with any acoustic emission. Even more, most of the peaks of electromagnetic intensity coincide with very low acoustic activity. These results are counterintuitive in the sense that all the mechanisms proposed until now directly relate electromagnetic events with the micro-cracking processes; our results suggest that there is a strong non-fracture component behind the origin of these emissions. Energy–duration maps also show discrepancies between acoustic and electromagnetic emissions: while the acoustic events clearly correspond to fracture events, electromagnetic emissions do not exhibit a power law relation.

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