ACOUSTIC EMISSION IN ROCK FRACTURE ANALYSIS

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ABSTRACT

Acoustic emission during deformation and failure of rocks in compression appears to be related to initiation and propagation of cracks, but also to dislocation glide, deformation twinning, grain boundary movements, frictional sliding along preexisting cracks. In order to distinguish between these events of different origins and to study the mechanism of deformation and failure of brittle and ductile rocks, the volumic strain and cumulative acoustic emission versus principal maximum stress were plotted during uniaxial compression test, and the frequency-peak amplitude relationship for the events were studied. Two rocks with different types of behaviour were tested. Analysing the parameters of the peak amplitude distribution with respect to the behaviour of the rock, we were able to distinguish between the acoustic events of different source mechanisms.

KEYWORDS

Rock mechanics; deformation; crack propagation; failure; acoustic emission; peak amplitude distribution; source mechanism.

INTRODUCTION

Few experiments in rock mechanics have been carried out in order to distinguish between the acoustic events according to the source mechanism. In previous studies, workers correlated acoustic emission to microfracturing and frictional sliding (Scholz, 1968a; Hardy and Kim, 1971; Perami, 1971).

During uniaxial compression, different regions are commonly observed (Fig. 1). In region 1, the axial stress-volumic strain and the axial stress-cumulative acoustic curves are convex downwards. This behaviour is attributed to the closing of microcracks. Frictional sliding along preexisting cracks and crushing of pores are expected to be the source of the acoustic activity during this stage. This region is not well observed for compact rocks. In region 2, the axial stress-volumic strain and the axial stress-acoustic emission curves are linear, the behaviour is quasi-linear elastic and few events occur. The other regions depend on the behaviour of the rocks. For brittle rocks with the help of the strain curve, Brace (1964) notes two more regions. In region 3, the lateral strain and consequently volumic strain (as $\Delta V/V = \varepsilon_1 + 2\varepsilon_2$) become non linear. Dilatancy appears, i.e. if the elastic volumic strain is not taken into account, rock increases in volume. Stable cracks open parallel to the direction of axial stress. In region 4, the axial strain becomes also non linear, cracks are supposed to become unstable. Scholz (1968a) found a good correlation between dilatancy and cumulative acoustic emission. During these stages, events are essentially attributed to initiation and propagation of cracks. Unstable crack propagation is characterized by a resulting increase in the amount of acoustic emission.

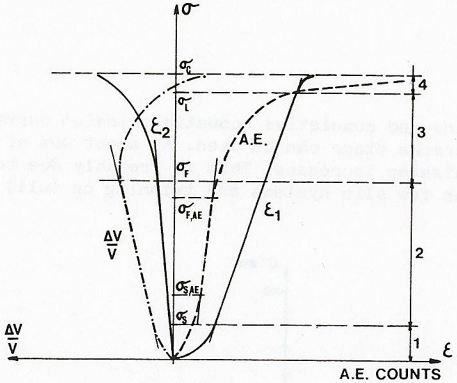

Fig. 1: Axial stress versus axial strain (ε_1), radial strain (ε_2), volumic strain and cumulative acoustic emission for a brittle rock.

For ductile rocks, beyond the elastic limit called the yield point σ_p, permanent deformation appear and the behaviour depends on rock type. During experiments on marble, Scholz (1968a) observed that acoustic emission begins at the onset of the yielding region and proceeds at a constant rate with no acceleration. Nevertheless, the relation between acoustic events and behaviour of ductile rocks is not well understood.

Mogi (1962), Scholz (1968b), Weeks, Lockner and Byerlee (1978) also studied the frequency-peak amplitude relation in order to try to gain a better understanding of seismic processes. They observed that the peak amplitude distribution obeys the Ishimota-Iida relation used in seismology:

$$n(a)da = ka^{-m}da$$

n(a) being the number of events detected with a peak amplitude between a and a + da, k and m being constants. M-value is compared with b-value of the Gutenberg and Richter relation:

$$\log N = a - bM$$

N being the number of earthquakes with a magnitude between M-dM and M+dM, a and b being constants. The value of m is related to the value of b by:

$$b = m - 1 \quad \text{(Suzuki, 1959).}$$

The interest of such studies was that changes in b-value were proposed as possible criterions for earthquake prediction. Scholz observed that b-value had a tendency to decrease as stress was raised. He also found that the frequency-peak amplitude relation for events occuring during frictional sliding and deformation of ductile rocks had a much higher b-value than that observed in brittle rocks. In order to further our understanding of the acoustic events, we used a more accurate apparatus in analysing acoustic events with particular attempt to eliminate background noise. Then we tried to correlate cumulative acoustic emission versus stress and peak amplitude distribution with macroscopic deformation and microscopic events observed on rocks during uniaxial compression tests.

ROCKS STUDIED

Results on two rocks, Senones Granite and Villette Limestone, are given in this paper. They were chosen because they exhibit two different behaviours during uniaxial testing. Senones Granite is a compact coarse grained rock, brittle dilatant under uniaxial test. Villette Limestone is a compact metamorphic limestone. This fine grained limestone has a ductile behaviour under uniaxial test. Description of the rocks, with the average value of the Young's modulus, of the Poisson's ratio and of the peak stress determined from seven samples of each rock, are given in table 1.

TABLE 1 Description of the Rocks

Rock	density gr/cm^3	d mm	modal analysis	E MPa	ν	σ_c MPa
Senones Granite	2.67	4-10	21. % Quartz	58000	0.3	155
			38.5% Orthose			
			30. % Plagioclase			
			2.5% Amphibole			
			8. % Biotite			
Villette Limestone	2.75	0.3	77. % Calcite	60000	0.2	105
			21. % Dolomie			

EXPERIMENTAL METHOD

Cylindrical samples of rock 7.90 cm long and 3.95 cm in diameter were tested under uniaxial compression at different strain rates. Steel discs the same diameter as the test specimen were inserted between the sample and the bearing plate of a servo-controlled hydraulic press in order to obtain a uniform stress distribution. Lateral and axial strain were measured with strain gauges mounted on samples. A micro-processor monitor data acquisition acquires data from strain gauges, load frame, counter of acoustic emission, every 30.10^{-6} strain, and sends them on a teletype-writer. The system used for monitoring acoustic events during experiments is a Dunegan 3000 series. It consists of a lead zirconate titanate (PZT) transducer, directly attached to the sample, a preamplifier, a high pass filter set at 100 KHz, an amplifier, a threshold detector which is set to provide a digital pulse when the amplitude of the amplified emission exceeds 1 volt, a digital counter which accumulates pulses, an amplitude detector set at a specified threshold which sends pulses proportionnal to the log of the peak burst amplitude of the non amplified signal, and a distribution analyser. The gain used during experiment was set at 95 dB. Then, axial, lateral, volumic strains and cumulative acoustic emission are plotted versus principal maximum stress. To study the peak amplitude relation, the distribution analyser performs a "per event" output and storage of conditioned acoustic emission signals according to the peak amplitude. At a selected stress level, the peak amplitude distribution is plotted on a XY recorder, the distribution analyser features the extremely wide dynamic range of 100 dB and a resolution of 1 dB. Then the memory is reset and the experiment continued. The value of m is calculated by the least square method.

EXPERIMENTAL RESULT

Senones Granite

Axial stress strains and axial stress cumulative acoustic emission curves are given in Fig. 2, and the peak amplitude distribution at three different stages in Fig. 4b and in Fig. 5. The stress strain curves correspond to a brittle rock behaviour with poor crack closure stage, stress axial strain being almost always linear. The onset of dilatancy, σ_f, determined with the axial volumic strain curve, and if we assume that the acoustic emission is related to the microfracturing in compact rocks (Scholz, 1968a; Perami, 1971), the onset of microfracturing, $\sigma_{f,ae}$, determined with the axial stress-cumulative acoustic curve are reported in Table 2.

TABLE 2 Onsets of Dilatancy and Microfracturing

Sample n°	σ_f/σ_c	$\sigma_{f,ae}/\sigma_c$
1	0.50	0.46
2	0.64	0.48
3	0.72	0.50
4	0.76	0.39
5	0.68	0.51
6	0.73	0.59

As the acoustic emission apparatus has a higher sensitivity than the strain gauges, and as it takes into account all the events occuring in the sample, whereas the strain measurement is local, the onset of microfracturing is determined with more accuracy. Before the onset of dilatancy there are a few events. They occur at a constant rate. The high m-value (Fig. 6) indicates that the events have low energy. The Ishimota-Iida relation is well correlated, the coefficient of correlation has a value of about 0.95. After the onset of dilatancy, acoustic emission increases gradually until failure. During this stage, axial cracks open at grain boundaries or at high angle grain interfaces (Tapponier and Brace, 1976). The Ishimota-Iida relation is no longer well correlated. At least one more peak appears in the distribution. An elementary distribution of higher energy events can be distinguished from one of lower energy events (Fig. 5). The value of the peak remains constant during the test within the 1 dB resolution of the distribution analyser. The relative number of high energy events increases as failure approach, so the m-value for the distribution of the lowest energy events decreases until failure (m-value was calculated during all the experiments with the low amplitude data in order not to be affected by the distribution of the highest energy events). The effect of the strain rate is shown on Fig. 6: the higher the strain rate, the lower is the m-value.

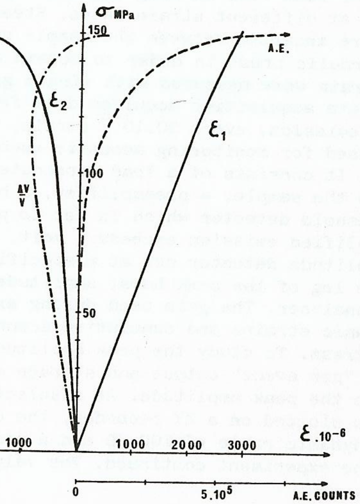

Fig. 2: Axial stress versus axial strain ($\mathcal{E}_1$), radial strain ($\mathcal{E}_2$), volumic strain and cumulative acoustic emission for the Senones Granite n°2

Villette Limestone

The axial stress-strains and cumulative acoustic emission curves are given in Fig. 3. Very poor closure of cracks stage can be seen. At about 40% of the peak stress, cumulative acoustic emission increases. This is probably due to deformation twinning in calcite. Calcite has few slip systems and twinning on (011) plan is common during uniaxial test (Nicolas and Poirier, 1976). The onset of the assumed twinning does not correspond with the yield point (Table 3), as it is observed on granite between σ_F and $\sigma_{F,AE}$. Beyond the yield point no dilatancy appears and the axial stress cumulative acoustic emission curve has a constant slope. The Ishimota-Iida relation is always well correlated and m-value decreases until the onset of dilatancy. During this stage it seems that twinning continues to proceed by nucleation and growth. After the onset of dilatancy, acoustic events are lower in energy.

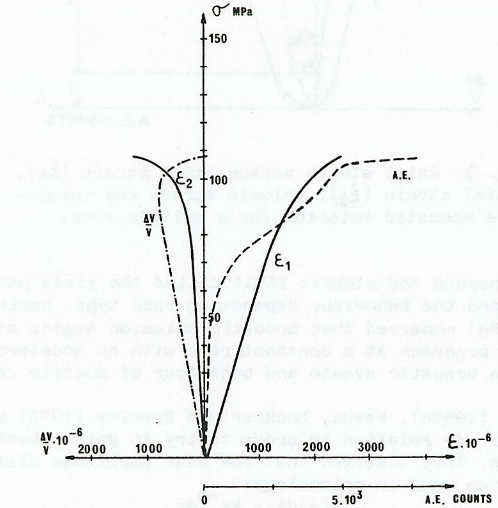

Fig. 3: Axial stress versus axial strain ($\mathcal{E}_1$), radial strain ($\mathcal{E}_2$), volumic strain and cumulative acoustic emission for the Villette Limestone n°1.

This fact is observed on the cumulative acoustic emission curve where the slope is higher, and on the peak amplitude distribution where m-value increases. This fact is never observed on brittle rock. This stage corresponds to the nucleation and propagation of shear related cracks along twin plans. Grain boundary sliding probably does not occur, working at a higher temperature. Critical yield bands are observed on the surface of the sample. Rupture develops by growth of shear related cracks which coalesce along one preferential plane. During this stage, the amount of acoustic emission increases considerably, m-value decreases to 2. . A peak in the amplitude distribution is never well observed during testing on Villette Limestone. The m-value is also affected by the strain rate (Fig. 6). It is noteworthy that during testing on limestone the amount of acoustic emission is about two order of magnitude lower than during testing on granite. This fact is characteristic of homogenous rocks.

TABLE 3 Onsets of Twinning and Ductility

Sample n°	σ_t/σ_c	σ_p/σ_c
1	0.41	0.66
2	0.41	0.63
3	0.33	0.66
4	0.40	0.59
5	0.45	0.61

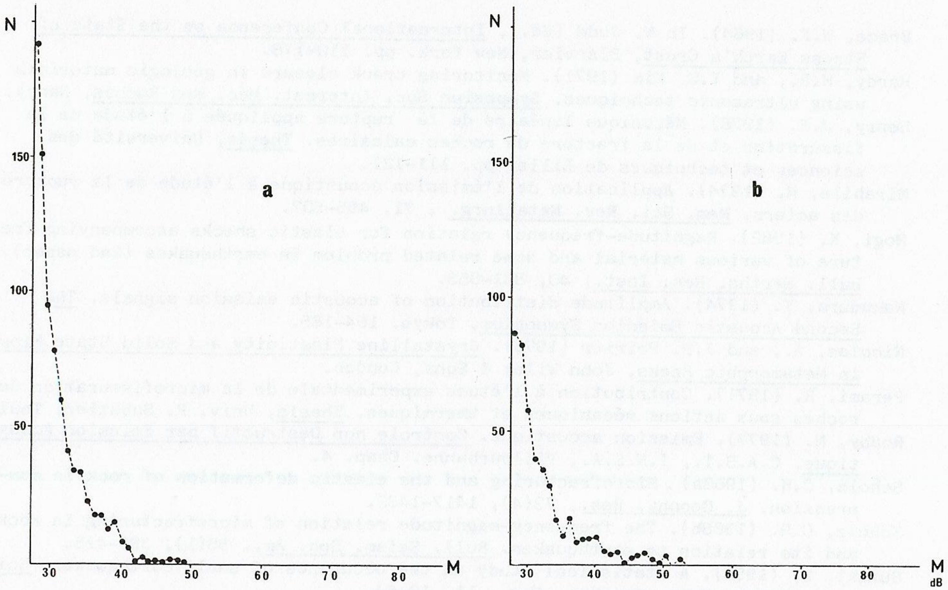

Fig. 4: Peak amplitude distribution
M: peak amplitude in dB; N: number of events.
a: for a Villette Limestone with σ/σ_c between 0.87 and 0.92
b: for a Senones Granite with σ/σ_c between 0.34 and 0.47

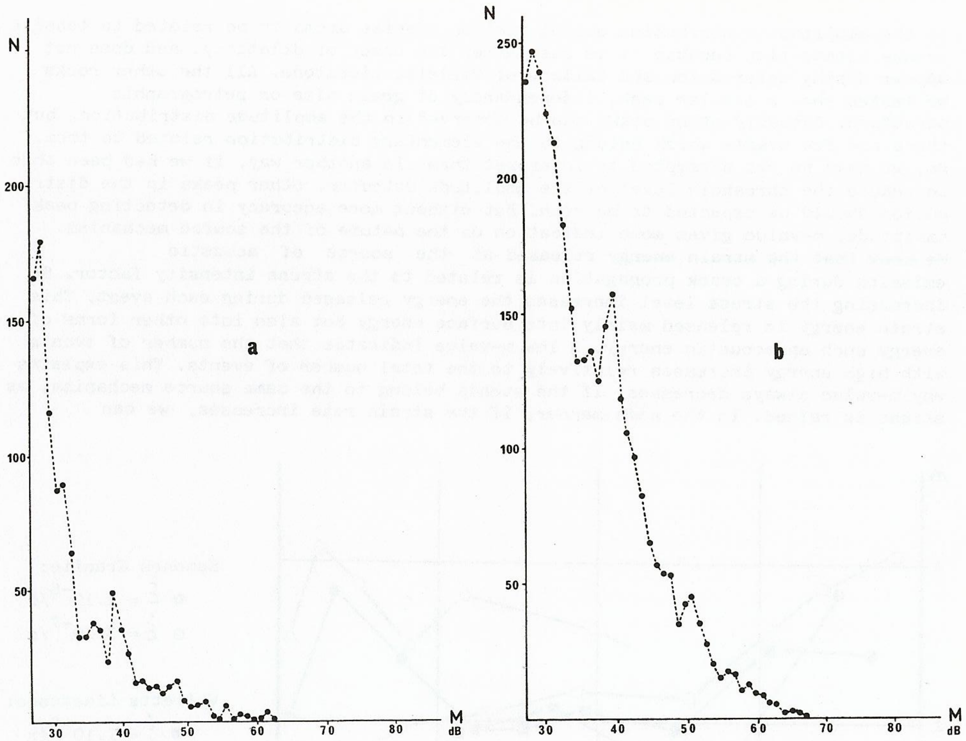

Fig. 5: Peak amplitude distribution
M: peak amplitude in dB; N: number of events.
a: for a Senones Granite with σ/σ_c between 0.70 and 0.74
b: for a Senones Granite with σ/σ_c between 0.98 and 0.99

DISCUSSION

The knowledge of the amount of energy released at the acoustic emission source has been the subject of many investigations but it is still something difficult to achieve. Several workers (Rouby, 1977; Mirabile, 1974) gave an idea of energy release for various mechanisms. In particular, it was found that energy release by dislocation movements were three or four orders of magnitude lower than energy release by propagation of tensile crack. In another way, the relationship between the observed peak amplitude and the amount of energy released at the source depends on the attenuation of strain waves in the medium, and of the pass band of the instrumentation used for monitoring acoustic emission. Note that the amplitude distribution is independent of attenuation if the signals have the same frequency spectrum. However, and in accordance with Nakumura (1974), the observed peak amplitude can be considered to be proportionnal to the square root of the energy incident on the transducer within the pass band of our equipment. The peak observed in the amplitude distribution during test on granite seems to be related to tensile cracks propagation because it is seen after the onset of dilatancy, and does not appear during deformation and failure of Villette Limestone. All the other rocks we tested show a similar peak, independantly of grain size or petrographic structure. Actually other peaks can be observed in the amplitude distribution, but there are few events which belong to the elementary distribution related to them. So, we have no yet attempted to interpret them. In another way, if we had been able to reduce the threshold level of the amplitude detector, other peaks in the distribution should be expected to be seen. But without more accuracy in detecting peak amplitude, m-value gives some indication on the nature of the source mechanism. We know that the strain energy released at the source of acoustic emission during a crack propagation is related to the stress intensity factor. So increasing the stress level increases the energy released during each event. This strain energy is released mainly into surface energy but also into other forms of energy such as acoustic energy. A low m-value indicates that the number of events with high energy increases relatively to the total number of events. This explains why m-value always decreases, if the events belong to the same source mechanism, as stress is raised. In the same manner, if the strain rate increases, we can assume that the stress intensity factor at the tip of a defect like a preexisting crack increases rapidly (Henry, 1978). The crack begins to grow with a higher stress intensity factor than if the strain rate was lower. So, increasing the strain rate, increases the energy released during each event. Other phenomena, such as the petrographic structure, the grain size, affect the m-value, but the main fact is that m-value depends on the source mechanism. Studying the m-value for the elementary distribution of low energy events, allows us to distinguish between several phenomena. We can observed that during the propagation of shear cracks, the m-value is about twice higher than during the propagation of tensile cracks. The high value of m, during propagation of shear cracks, indicates that this mechanism releases few strain energy. A high m-value is also observed during the elastic stage of granite where frictional sliding along preexisting clivage planes occurs, in particular in biotite and felspar. During the elastic stage of Villette Limestone, not enough events were generally recorded in order to have a significant m-value. But each time we have been able to determine m-value, it was near to the value observed on granite. The low m-value observed during twinning can be explained by this deformation mode. Twinning is a very rapid deformation which occurs by burst (Nicolas and Poirier, 1976).

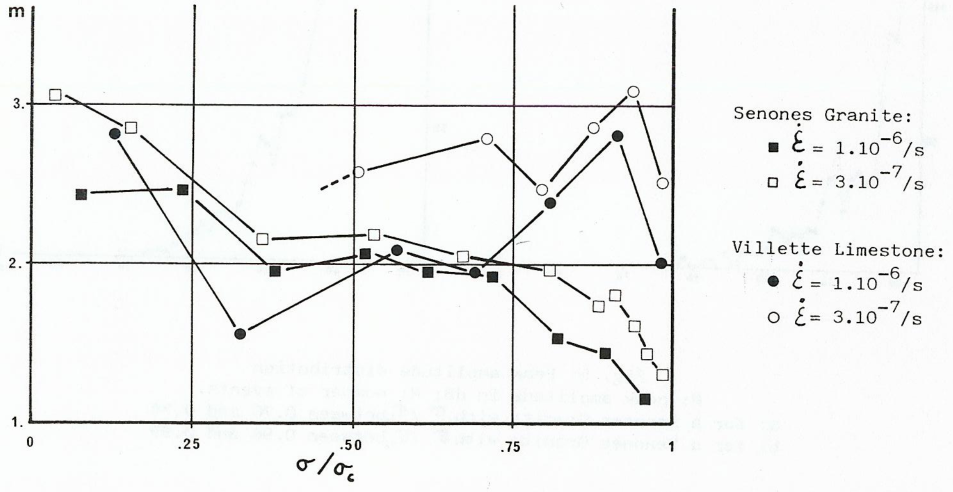

Fig. 6: m-value versus σ/σ_c .

CONCLUSION

Studying the frequency peak relationship seems to be a good way to distinguish between the source mechanisms of acoustic events. It seems also to have an application on predicting the failure mode in rock mechanics, since during tests on granite and limestone two different evolutions of m-value, related to the mechanism of deformation and failure, were observed. Even if in this paper the results shown are only qualitative, we hope to obtain quantitative results, in particular if the relation between the elementary distribution of high energy events and tensile cracks is comfirmed. More experiments are needed and we are now looking at the ductile-brittle transition which will be certainly rich in information in comparaison with the acoustic events.

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