ACOUSTIC EMISSION AND FAULT FORMATION IN ROCKS

by

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Abstract

Acoustic emission events were recorded during failure of sandstone and granite samples that were deformed under a confining pressure of 1 kb. At a differential stress higher than about 90 percent of the ultimate strength of one of the sandstone samples, the hypocenters of the events tended to cluster on a plane that coincided with what eventually became the fault plane. During another experiment in which a sample of sandstone was deformed at a much slower rate, clustering of the events on the fault plane occurred only in the post-failure region. In both the experiments that were carried out with granite, there was no tendency for the acoustic emission events to cluster on the fault plane before the ultimate strength of the rock was reached. Malfunction of our data collection system during violent failure of the granite samples prevented us from determining whether or not clustering of the events occurred in the post-failure region with granite.

Introduction

Understanding the failure mechanism of rock has been a major problem in rock mechanics. Wawersik and Fairhurst (1970) approached the problem by studying the fracture pattern produced in rocks during their deformation. They concluded that, at least under uniaxial stress, the fractures which occurred prior to macroscopic failure were tension fractures oriented with their long axis parallel to the direction of maximum compressive stress. They found that shear failure was not developed until after the maximum in the stress strain curve had been reached. Wawersik and Brace (1971) studied the fracture patterns that were developed during failure of rocks under confining pressure. They concluded that at pressures above about 1500 bars, the ultimate strength of rocks such as granite and diabase was controlled by faulting but at confining pressures below this, faulting occurred only in the post-failure region. Scholz (1968) on the other hand approached the problem by studying the location of the acoustic emission events which occur during rock deformation. He concluded that with granite, when the uniaxial stress exceeded about 90 percent of the failure stress, the microfracture activity clustered along what eventually became the macroscopic fault plane. Thus his results would suggest that fault formation occurred at a stress below the ultimate strength of the rock. This conclusion would be in disagreement with the conclusions of Wawersik and Fairhurst (1970) and Wawersik and Brace (1971).

Scholz's results have been questioned by Savage (1970) who pointed out that the accuracy of the recording equipment used by Scholz was insufficient to give much confidence in the location of the acoustic emission events. Thus whether fault formation occurs in the pre- or post-failure region is still open to question.

We have developed an apparatus to record acoustic emission during the deformation of rock samples under triaxial compression. Due to our very large sample size and very precise electronic timing we are able to locate the hypocenters of the acoustic emission events with high accuracy. Although the results that we have obtained to date do not completely resolve the question of whether fault formation occurs before or after the ultimate strength is reached, we have collected some data during the deformation of samples of granite and sandstone which should be of interest to workers in the field of acoustic emission and rock mechanics. The purpose of this paper is to present the results and discuss their significance.

Experimental Method and Results

Two cylindrical samples of the Weber sandstone and two samples of Westerly granite each 19 cm long and 7.6 cm in diameter were jacketed and deformed under a constant confining pressure of 1 kb. During each experiment the differential stress was raised in discrete steps until the ultimate strength was reached and a through-going fault formed. Figure 1 shows differential stress as a function of time for the four experiments. The two sandstones are plotted in Figure 1A and the two granites in Figure 1B. Since the sandstone creep experiment took place over a much longer time period than the other experiments, the time scales of the two plots are quite different. For purposes of comparison, the first sandstone experiment is replotted in Figure 1B. At each step the differential stress was held constant and the acoustic emission was recorded. The hypocenters of the events were computed, plotted, and contoured using the method described in the paper "Acoustic emission during fluid injection into rock" by Byerlee and Lockner which appears elsewhere in this volume.

The contours of the data collected during all four experiments are shown in Figures 2 through 5. Each figure consists of 6 sets of contours. Each set is constructed from a compilation of the data collected at various stress levels. The stress levels and time interval over which the stress was held constant is shown below each contour set.

All the hypocenters were projected onto a plane normal to the macroscopic fault plane formed during catastrophic failure. In each figure the trace of the fault plane is shown in the lower right-hand set of contours by the heavy solid line.

Figure 2 shows that there was a concentration of acoustic emission activity at the lower end of the sample. We first thought that this

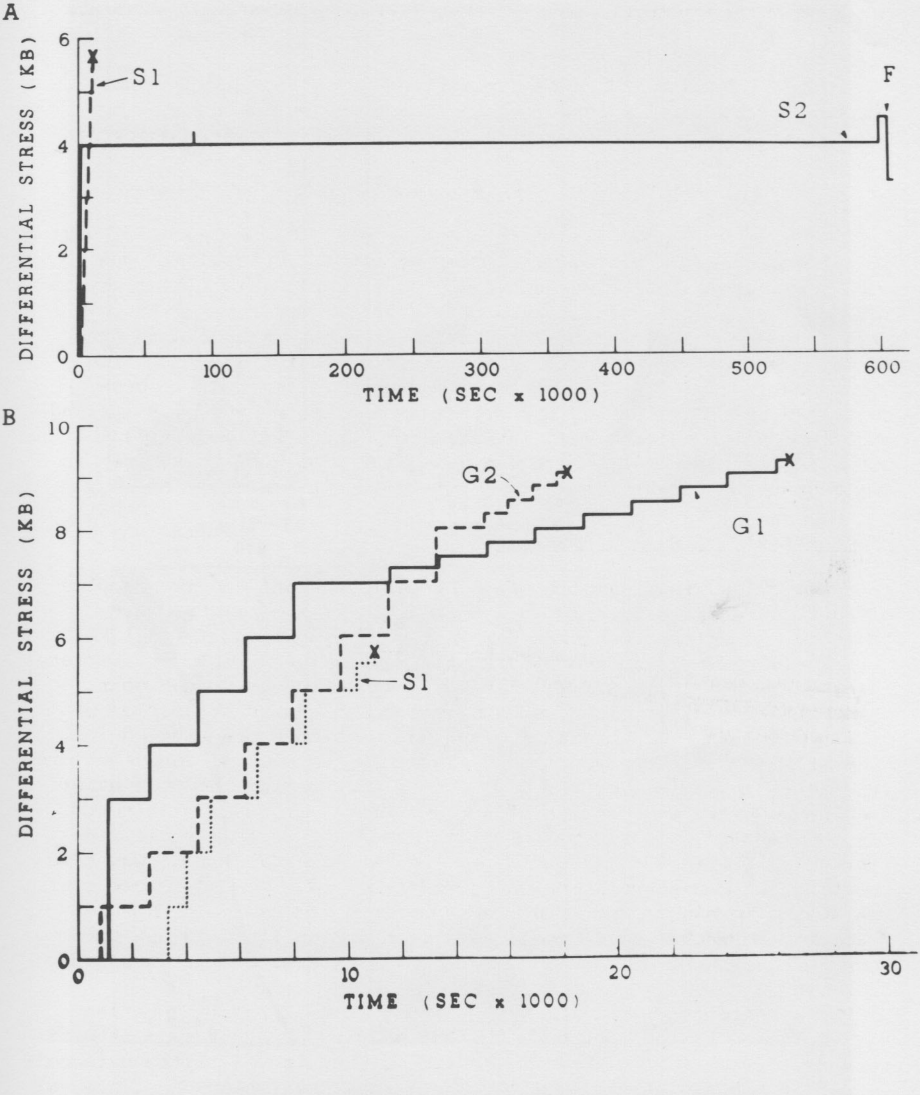


Fig. 1. A plot of differential stress as a function of time A (for experiments S1 and S2,) and b (for experiments S1, G1, and G2). Macroscopic failure in experiments S1, G1, and G2 is designated by X. Development of macroscopic fault plane in experiment S2 occurs at point F.

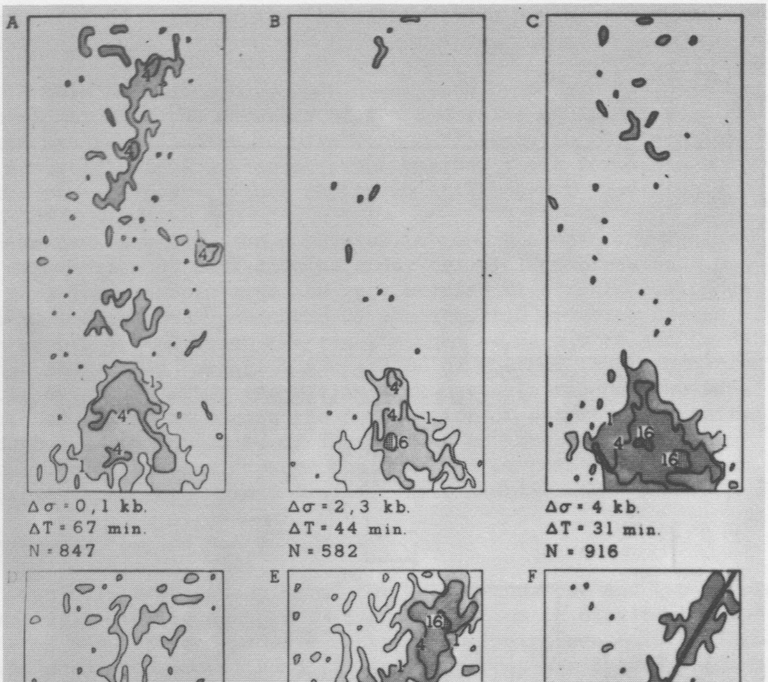


Fig. 2. Contours of hypocenter location density for experiment S1, with the Weber sandstone, projected onto the plane normal to the macroscopic fault plane. The trace of the fault is shown in Figure 1F. Failure occurred after Figure 2F.

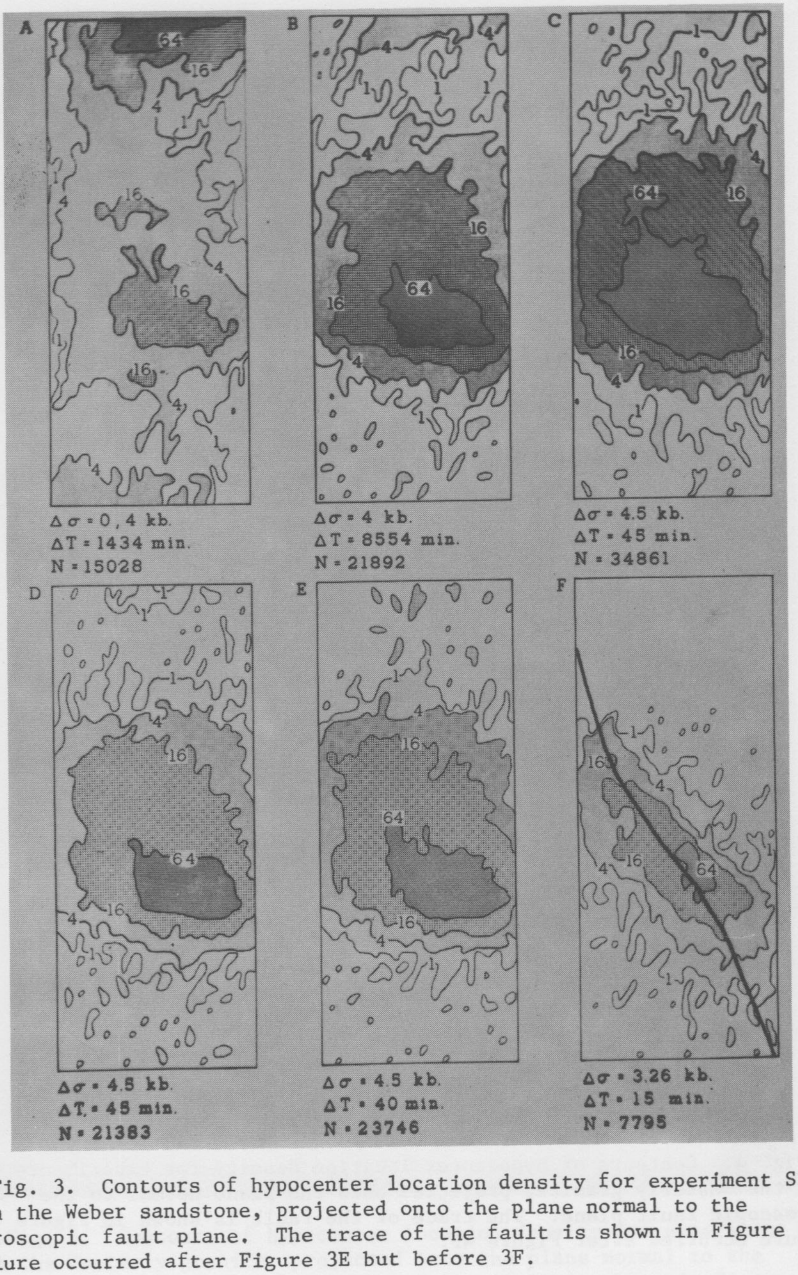
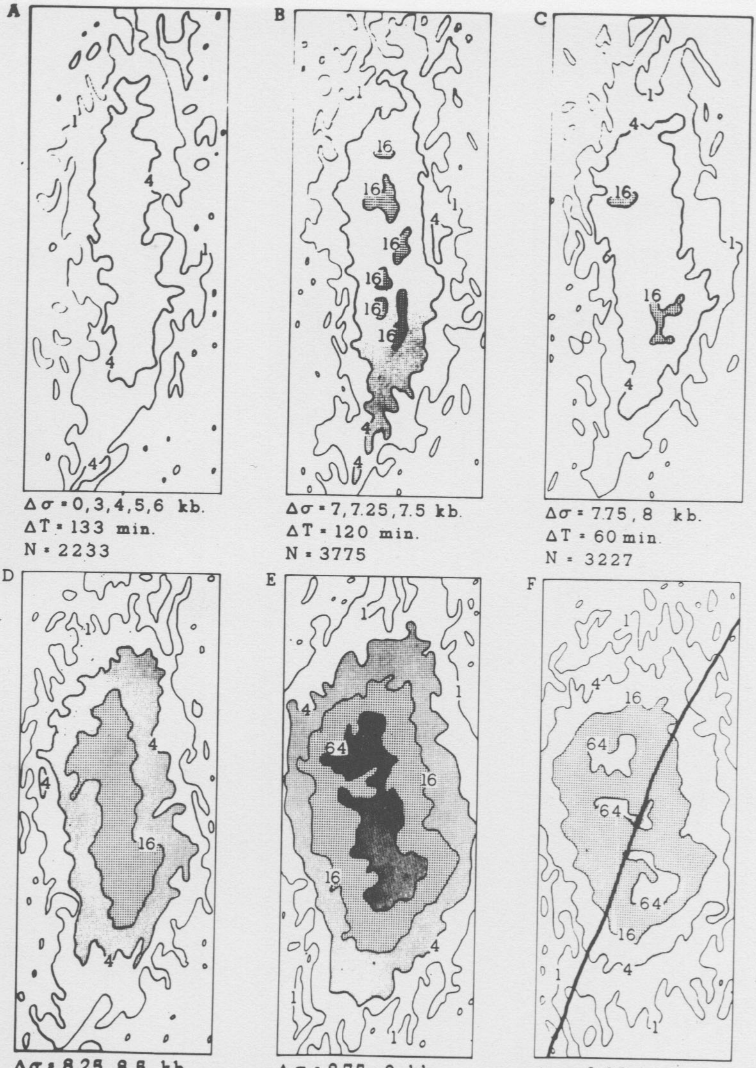


Fig. 3. Contours of hypocenter location density for experiment S2, with the Weber sandstone, projected onto the plane normal to the macroscopic fault plane. The trace of the fault is shown in Figure 3F. Failure occurred after Figure 3E but before 3F.



A: $\Delta\sigma$ = 0,3,4,5,6 kb.
ΔT = 133 min.
N = 2233

B: $\Delta\sigma$ = 7,7.25,7.5 kb.
ΔT = 120 min.
N = 3775

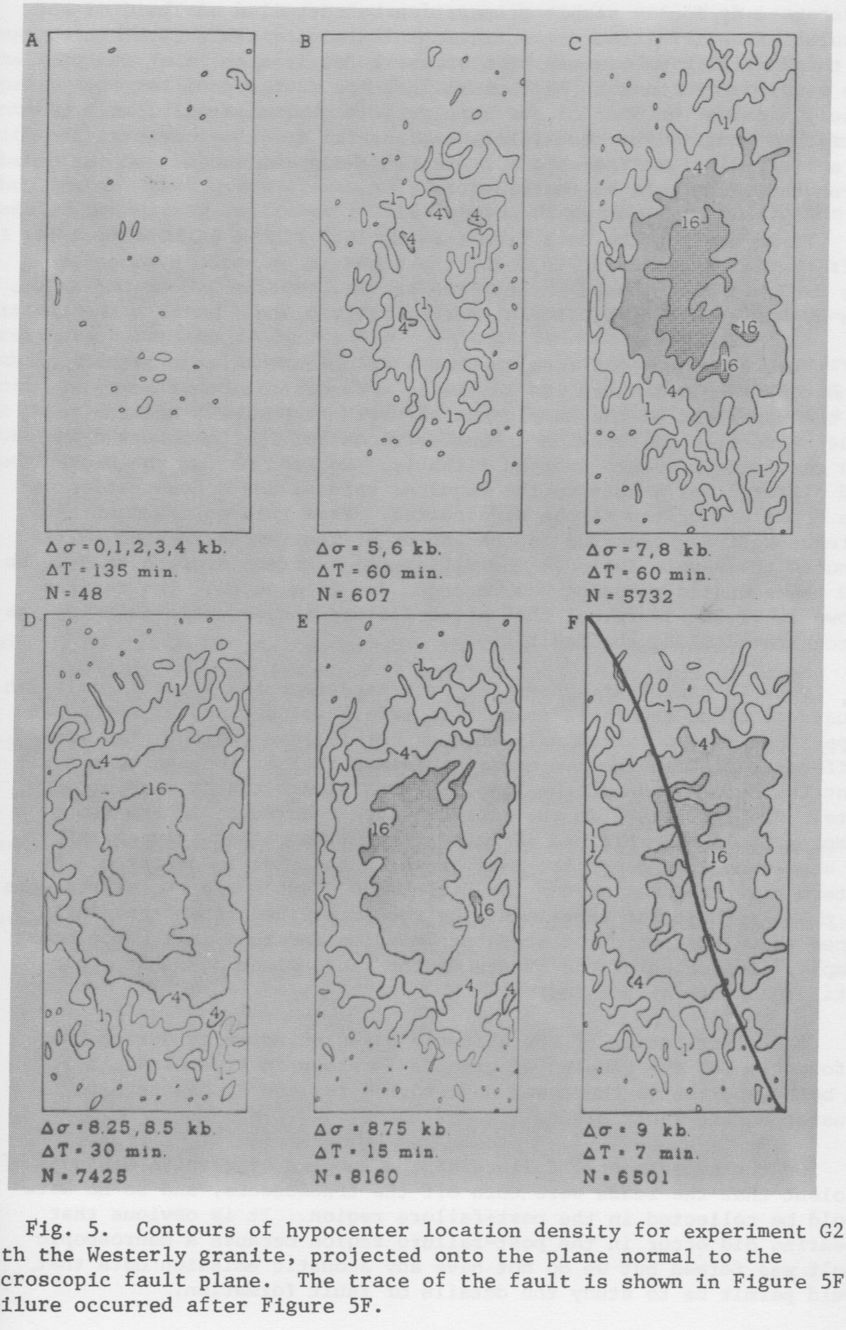
C: $\Delta\sigma$ = 7.75, 8 kb.
ΔT = 60 min.
N = 3227

D: $\Delta\sigma$ = 8.25, 8.5 kb.
ΔT = 60 min.
N = 6852

E: $\Delta\sigma$ = 8.75, 9 kb.
ΔT = 60 min.
N = 23385

F: $\Delta\sigma$ = 9.25 kb.
ΔT = 7.5 min.
N = 19062

Fig. 4. Contours of hypocenter location density for experiments G1, with the Westerly granite, projected onto the plane normal to the macroscopic fault plane. The trace of the fault is shown in Figure 4F. Failure occurred after Figure 4F.



A: $\Delta\sigma = 0,1,2,3,4$ kb.
$\Delta T = 135$ min.
$N = 48$

B: $\Delta\sigma = 5,6$ kb.
$\Delta T = 60$ min.
$N = 607$

C: $\Delta\sigma = 7,8$ kb.
$\Delta T = 60$ min.
$N = 5732$

D: $\Delta\sigma = 8.25, 8.5$ kb.
$\Delta T = 30$ min.
$N = 7425$

E: $\Delta\sigma = 8.75$ kb
$\Delta T = 15$ min.
$N = 8160$

F: $\Delta\sigma = 9$ kb.
$\Delta T = 7$ min.
$N = 6501$

Fig. 5. Contours of hypocenter location density for experiment G2, with the Westerly granite, projected onto the plane normal to the macroscopic fault plane. The trace of the fault is shown in Figure 5F. Failure occurred after Figure 5F.

was caused by faulty sample preparation but detailed analysis of our results showed that the concentration of activity was axisymmetric. If this activity was caused by a stress concentration, that end of the sample would have to be conical in shape. This does not seem likely because the ends of our samples were ground parallel with a surface grinder. The most likely explanation for the concentration in activity is that the sample contained a flaw which lowered the strength of the rock in that region.

If we neglect the data from this region, Figure 1 shows that at differential stresses up to 5 kb, the acoustic emission hypocenters are randomly distributed through the sample. But at 5.5 kb and above, the events tended to cluster along the fault plane.

Figure 3 shows the results that were obtained with a second sandstone sample. There was initially a concentration of activity at the upper end of the sample but after the experiment had run for 1434 minutes, a malfunction in our servocontrol system occurred and the confining pressure dropped slightly. On readjusting the pressure and differential stress to the required values, the concentration at the upper end of the sample disappeared. From then on the most intense activity occurred in the center of the sample. After 10,118 minutes the sample failed. The differential stress dropped to 3.26 kb and the acoustic emission was recorded for 15 minutes. The results shown in Figure 3F reveal that after failure the acoustic emission was concentrated along the fault trace.

Thus in the first experiment with sandstone the acoustic emission clustered along the fault trace before failure, but in our second experiment this occurred only in the post-failure region. The major difference between the two experiments was that in the second experiment the deformation of the sample was carried out at a much slower rate. The difference in the microfracture occurrence in the two samples could be explained if the distribution of acoustic emission in sandstone depends on the rate at which the rock is deformed. An alternative explanation for the difference between the two experiments is that in the first experiment the rock contained flaws that influenced the distribution of acoustic emission and that in a homogenous sample, clustering of the events on the fault plane does not occur until the post-failure region.

The distribution of the acoustic emission activity during the deformation of the samples of granite is shown in Figures 4 and 5. In both experiments there was no tendency for the hypocenters to cluster on the fault plane.

In the experiments, failure of the samples of granite was so violent that the leads were torn off the transducers, and so no data could be collected in the post-failure region. It is obvious that shearing did occur in the post-failure region because a macroscopic fault was formed but we do not have any acoustic emission data that would permit us to study the details of fault formation.

In both of the experiments with granite and in one of the experiments with sandstone, the most intense activity was in the center of the sample. In studies of the fracture patterns produced in rocks during deformation Wawersik and Fairhurst (1970) found that the most intense fracturing occurred in the center of the samples, agreeing with our acoustic emission data. The most likely explanation for the phenomenon is the one advanced by Wawersick and Fairhurst (1970). They suggest that crack growth is suppressed at the ends of the samples because of restraint in the lateral direction due to friction at the rock-loading device interface.

In two experiments performed on granite under similar loading histories, we found no indication of pre-failure clustering of microfractures along the failure plane. This is in disagreement with Scholz's findings. In one of two sandstone experiments, microfracture activity did localize on the fault plane before failure. However, it is possible that this was due only to some local defect in the sample. More experiments of this nature need to be performed to clarify this question.

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