Bulletin of the Seismological Society of America, Vol. 68, No. 2, pp. 333-341, April, 1978

CHANGE IN *b*-VALUES DURING MOVEMENT ON CUT SURFACES IN GRANITE

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ABSTRACT

A large granite sample containing a saw cut, modeling a natural fault, was triaxially loaded at confining pressures up to 1000 bars. Fourteen violent slip events accompanied by foreshock and aftershock sequences occurred under constant strain rate loading. From digitally recorded acoustic emission, locations and amplitudes were determined for nearly 8,000 microseismic events.

Plots of log amplitude versus log frequency of microseismic events were drawn for three periods between each slip event, termed foreshock, aftershock, and background. These plots indicate that the *b*-value is lower during foreshocks than for periods between events, implying increased average amplitude of microseismic activity just before slip. These experimental results suggest that it may be possible to devise an earthquake warning system based on changes in *b*-values in active tectonic regions. It has been suggested that according to the dilatancy-diffusion model, *b*-value would decrease prior to earthquakes. In our experiment, however, the rock was dry.

INTRODUCTION

Changes in such geophysical parameters as seismic velocity, seismicity, and *b*-value have been proposed as possible earthquake precursors. However, the difficulty of measuring these parameters in the field has often yielded ambiguous results. An example of this ambiguity is found in changes in the V_p/V_s ratio. Several authors have reported changes in this ratio before earthquakes (Aggarwal *et al.,* 1973; Semenov, 1969; Whitcomb, 1973; others), but for a number of earthquakes the search for such changes has been unsuccessful or ambiguous (Allen and Helmberger, 1973; Boore *et al.,* 1975; Lockner *et al.,* 1977). In the case of *b*-values, it is necessary to include a large number of earthquakes in the calculation in order to obtain meaningful results. A years' time may be required to collect a sufficient sampling of events (Wyss and Lee, 1973).

To eliminate some of the ambiguities of field measurements, we have performed an experiment under controlled laboratory conditions similar to those existing in the Earth. A natural fault was modeled by a saw-cut in a large sample of dry granite. Under constant strain-rate loading, 14 stick-slip events occurred, and we recorded arrival times and amplitudes of nearly 8,000 microseismic events that took place during all phases of stick-slip. With this large data-base, using methods similar to those used by seismologists, we calculated locations of events, average frequency of events, and *b*-values for all parts of the stick-slip stress cycle.

EXPERIMENTAL METHOD

A cylindrical sample of Westerly Granite 19.5 cm long and 7.62 cm in diameter was prepared with a saw-cut inclined at 30° to the axis of the cylinder. The saw-cut surfaces were carefully ground to ensure flatness. The two halves of the sample were assembled and a copper sleeve 0.13 mm thick was pressed on to keep them together during handling. The sample was then placed in a polyurethane sleeve to isolate it from the confining fluid. Six piezoelectric transducers with resonant frequency of 600 kHz were cemented to the sample with epoxy to monitor acoustic emission from the rock.

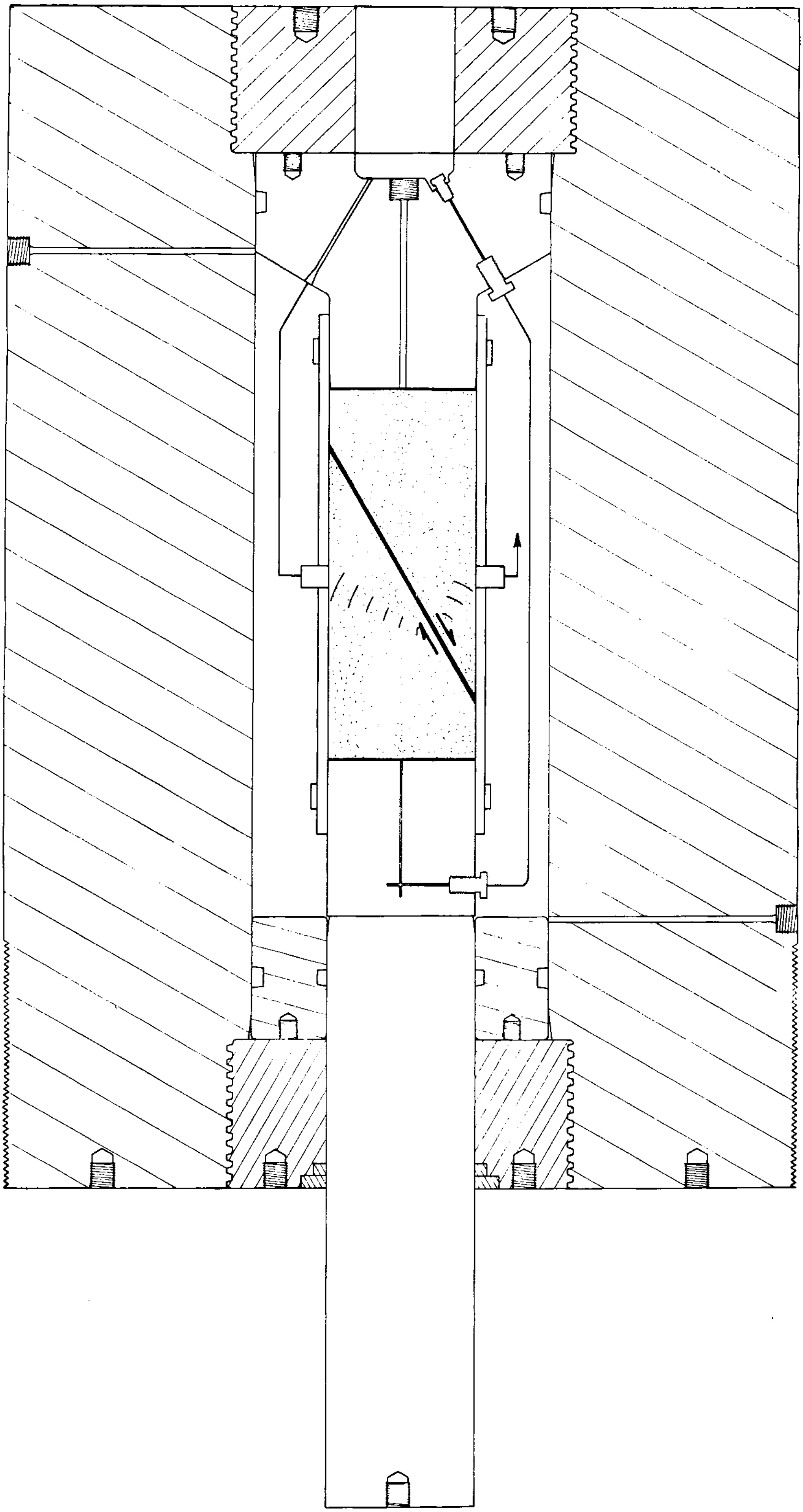

FIG. 1. A schematic diagram of the sample set-up showing the positions of two of the six transducers. The other four transducers are located near the ends of the sample. The position of the saw-cut, oriented at 30° to the axis of the sample, is also shown.

After being mounted in a pressure vessel, the sample was held at constant confining pressure by a servo-controlled hydraulic pump. A piston was advanced at constant strain rate to apply an axial load which produced stick-slip sliding on the saw-cut surface. A total of 14 stick-slip events occurred at three confining pressures: nine at 500 bars, three at 750 bars, and two at 1,000 bars. With a strain rate of 1.7×10^{-5} sec^{-1}, sudden slip occurred at about 10-min intervals at 500 bars confining pressure, about 15 min at 750 bars, and about 20 min at 1,000 bars.

The outputs of the six transducers attached to the sample were amplified and fed into an electronic timing system. In this system, each time a microfracture event occurs the seismic waves that are produced travel to the six transducers. The timing system measures the relative arrival times at each of the six transducers, and records the information in digital form on magnetic tape. Also, the maximum amplitude during the first 7.0 μsec after the first arrival is digitized and recorded for each transducer. These amplitudes are cataloged in 100 amplitude levels from 0 to 99. All amplitudes less than 1 are recorded as 0 and those over 98 are recorded as 99. A burst of up to 32 events can be recorded in about 2 msec for a short term repetition rate of over 16,000/sec. The long-term repetition rate is limited by the transfer time from buffer memory to tape and is about 300/sec, or about 18,000 acoustic emissions per minute. A computer program calculates the location of each microseismic event from the acoustic emission data using an iterative technique employed by seismologists in locating earthquake hypocenters. This program also calculates the origin time and seismic wave velocity. For more details of this process, refer to Byerlee and Lockner (1977).

With the amplitude data collected at the two stations closest to the center of the sample, m-slopes were calculated in order to investigate the possibility of a change in this parameter before sudden slip on the saw-cut. The m-slope is given by the Ishimoto-Iida relation

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

where $n(a)$ is the number of events recorded at a particular seismic station with maximum trace amplitude between a and $a + da$, and k and m are constants (Ishimoto and Iida, 1938). This equation produces a straight line with a slope of $-m$ when plotted on log-log graph paper. Several studies have shown that earthquakes follow this relationship quite closely (Ishimoto and Iida, 1938; Suzuki, 1955, 1959; and others).

If the events recorded are from a finite volume and if the amplitudes at the hypocenters follow the Ishimoto-Iida relation in each elementary volume with uniform exponent m, it is possible to show that the relation holds independently of the station at which the events are recorded, the spacial distribution of events and the particular attenuation function that holds in the area of study. If these conditions are satisfied, the m-slope will be the same at the recording station as that measured at the hypocenters, making it possible to determine the frequency-magnitude relation from amplitudes measured at a single station (Suzuki, 1953).

It has also been shown (Asada *et al.*, 1951) that b-value, determined from log $N(M) = a - bM$ (Gutenberg and Richter, 1949) is related to m-slope by $b = m - 1$. Therefore, since the log of the amplitude at the hypocenter is proportional to the magnitude, the b-slope can be determined from observations of amplitude at a single station.

Another method for calculating b-value is the maximum likelihood estimate (Aki, 1965), given by

$$b = \frac{\log_{10} e}{\left(\sum_{i=1}^{n} \log a_i\right)/n - \log a_0}.$$

Here a_0 is the smallest amplitude for which there is complete detection and n is the number of events larger than a_0. This method assumes that there is no upper limit on amplitude; however, our equipment records amplitudes up to a limit of 99. This means that this method is not applicable to our data.

RESULTS

Figure 2 shows average amplitude, acoustic emission rate, and differential stress for a time period including the second and third slip events, indicated by vertical dashed lines, at 500 bars confining pressure. The differential stress was recorded continuously by a load cell in the piston applying the load. The values of the other parameters are the results of measurements made on individual microseismic events,

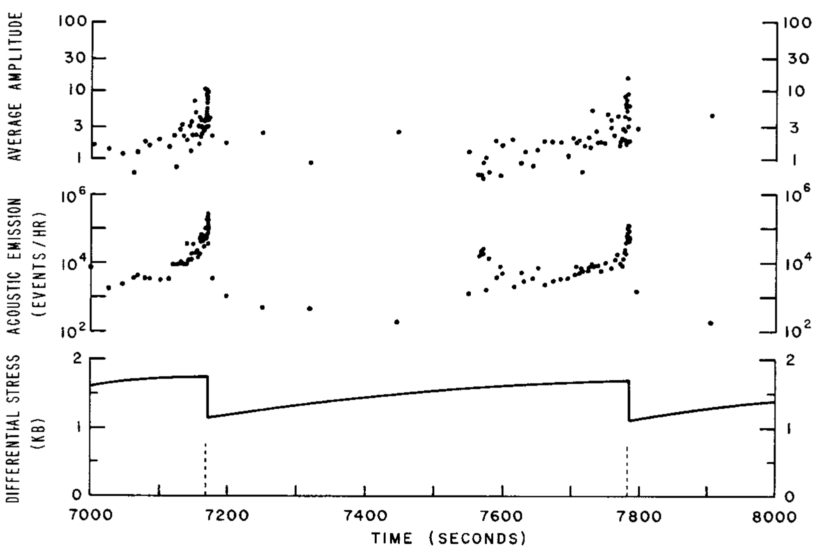

FIG. 2. Parameters measured during the experiment are plotted for a time period including two stick-slip events, shown by vertical dashed lines. Differential stress was recorded continuously by a load cell in the piston applying the load. The other values are calculated from individual microseismic events, with each point representing the average value of ten consecutive events.

and averaged over 10 events. Since the frequency of events varied over several orders of magnitude, the time-period represented by each point in Figure 2 varies from less than 1 sec to more than 100 sec.

The axial stress drop for each event at a given confining pressure was nearly constant. At a pressure of 500 bars the stress drop was about 550 bars, 690 bars at 750 bars confining pressure and 930 bars at 1000 bars confining pressure. While the stress drop at a given confining pressure remained nearly constant, the magnitudes of the stresses before and after slip changed. At 500 bars confining pressure, these stresses decreased with each event for the first five events, and were relatively constant thereafter. At 750 and 1000 bars, the stresses before and after slip increased with each event, and did not reach a steady value within the space of the small number slip events at these pressures.

The acoustic emission rate, shown in the middle graph of Figure 2, increased to a peak of about 10^5 events/hr before slip and dropped rapidly after slip. A surprising result is that the frequency does not rise smoothly. About 230 sec before the third event the frequency jumped by a factor of 80 to a peak of 10^4 events/hr, settled back to just under 10^4, and finally rose to about 10^5 at the time of failure. Of the 13 events for which this information is available, nine rose sharply to a peak or a plateau 200 to 300 sec before failure. In two of the four events that did not display this behavior strongly, it appears that the same phenomenon was occurring, but simply was not so abrupt.

The top graph in Figure 2 shows average amplitude, in this case the average value of the log of the amplitude observed at one of the stations in the center of the sample. The graph shown is typical of the entire experiment, with a relatively constant, low amplitude level for most of the time between stick-slip events and a peak just before slip. The average reached about half of its eventual peak value about 30 to 100 sec before slip, and fell to a low level very quickly after slip.

Because the amplitudes used are those measured at a single station, the positions of the events will affect the average amplitude. A cluster of events occurring very near the station might show a change in average amplitude having no relation to

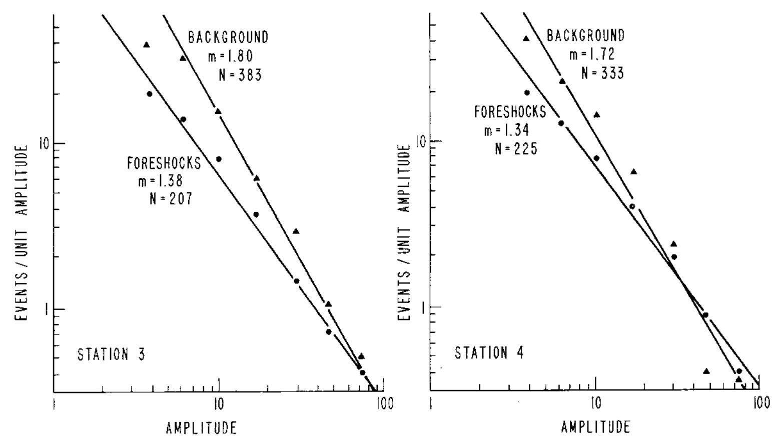

FIG. 3. The change in m-slope between background and foreshock microfractures prior to the first four stick-slip events is illustrated. Slopes are calculated by a least-squares fit. Stations 3 and 4 are the two transducers located at the center of the sample.

changing conditions in the rock. A much better measure of the average amplitude is provided by m-slope because, within the constraints mentioned earlier, it has no dependence on event location. Also, as discussed in connection with the maximum liklihood estimate of b-value, the finite range of our amplitude data means that average amplitude is not representative of m-slope.

The standard method for estimating m-slope is to make a least-squares fit to the amplitude-frequency data. Normally, the data is divided into equal amplitude classes when calculating m-slope. Because there are so few events in the large amplitude classes, and because a least-squares estimate of the slope is highly sensitive to errors in the end-members, this method gives an unreliable estimate of m-slope. Accordingly, we divided the data into equal classes of log amplitude rather than equal classes of amplitude. In this way, we averaged our data over larger intervals at high amplitudes where data is sparse, thus reducing the random variations in this part of the data to which the least-squares method is sensitive. When this is done, as in Figure 3, the units for the vertical axis become number of events per unit amplitude.

Because there was insufficient data to make reliable estimates of m-slope for each individual stick-slip event, data from events occurring under identical conditions were grouped together and the m-slope was calculated from all the data taken together. The m-slope was calculated for four groups of data: The second through the fourth stick-slip events at 500 bars, the fifth through the ninth events at 500 bars, the three events at 750 bars, and one event at 1,000 bars.

We divided the time between each event into three periods: The 10 sec before each event were called foreshocks, 200 sec after were called aftershocks, and the remaining time between events was termed "background". For each of these periods, m-slopes were calculated, one for each of the two stations in the center of the sample. Figure 3 shows an example of our data for these two stations, foreshocks and background.

The results are shown in Figure 4. The calculations for aftershocks are of questionable accuracy, but the results show clearly that m-slope was lower during the foreshock periods than it was during the background periods. This confirms the idea that peaks of average amplitude observed just prior to stick-slip are

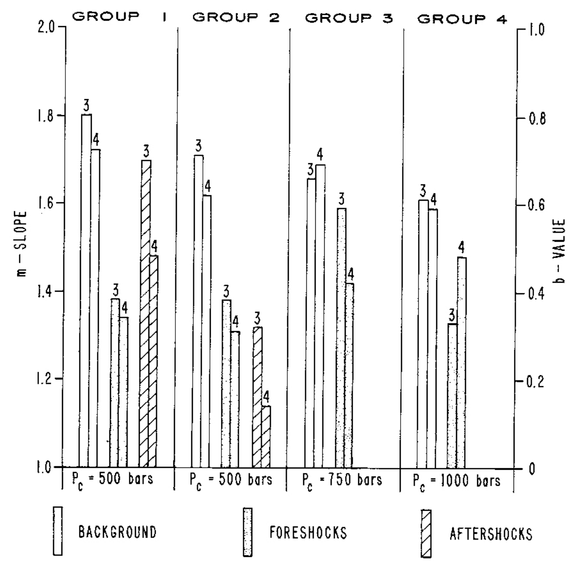

FIG. 4. The results of the m-slope calculations for all four groups of slip events are shown. The calculations for aftershocks have large uncertainties, but these results show that m-slope is consistently lower during the foreshock periods than during background periods. "3" and "4" refer to stations 3 and 4 located at the center of the sample.

actually caused by a relative increase in the number of large amplitude events rather than by an unrelated effect, such as a special bias in the spatial distribution of microfractures.

Suzuki (1958) suggests that even with the total size of the sample around 1,000, differences among estimates of m-slope for the same data set may be as large as 0.4, but this conclusion assumed equal-sized amplitude classes, with the result that high-amplitude classes having very few events would tend to be in great error. Since the least-squares method is very sensitive to the points near the ends of the sample, a large error in the high amplitudes can be expected to cause large differences in the values of m-slopes calculated by this method.

However, the results shown in Figure 4, with the exception of the aftershocks, display much better consistency than this, the difference between two estimates often being less than 0.1. To test this intuitive feeling, a t-test of the significance of the difference between background and foreshock b-values was performed. In performing a t-test, it is assumed that the data are normally distributed and that the variances of two values being compared are equal. Neither assumption is satisfied in this case, but deviations from normality for large sample sizes is probably small and calculated sample variances were generally within a factor of two. For the six background-foreshock pairs in the first three groups, the t-test indicates that the b-values are different at greater than 95 per cent confidence level. Group four does not show significant difference, but it is interesting to note that this group follows the same pattern of low b-value before slip. This generally high level of significance may be a result of averaging in the high amplitudes or it could be that our data, taken under ideal laboratory conditions, was more consistent than field measurements of seismic activity.

Because the graph of average amplitude starts to increase more than 100 sec before slip, one might expect that the foreshock period could be extended to 30 to 50 sec. Consequently, we calculated the m-slope for the same data as in Figure 4 using a 30-sec foreshock period instead of 10 sec. This tended to reduce the difference between m-slopes for foreshocks and background events, leading us to the conclusion that the change in m-slope observed before slip is relatively sudden.

DISCUSSION

Mogi (1962) and Scholz (1968) derived the Ishimoto-Iida relation giving m-slope from equations giving the energy released by a propagating crack and the probability that a crack will stop growing at a given size. According to their derivations, anything that changes this probability will also change the m-slope (or b-value). Since increasing the applied stress increases the driving force on a crack, at higher stress cracks should propagate farther, on the average, than at low stress, giving rise to a lower b-value at high stress. We believe that this is responsible for the changes observed here. Wyss and Lee (1973) suggested that dilatancy just before an earthquake could cause changes in b-value through dilatancy hardening. By Mogi's and Scholz's derivations, this could contribute, but our results indicate that fluids and dilatancy are not necessary to explain the phenomenon.

As the average stress in the rock increases, more and more areas will be at stresses above the local failure stress. Thus, it is not surprising that the acoustic emission rate increases as the stress rises before stick-slip. On the other hand, this cannot explain the peak in Figure 2 occurring 230 sec before slip. We believe there are at least two explanations for this phenomenon. It could be caused by a low-friction patch on the saw-cut that slips at a stress below the frictional strength of the saw-cut, thereby causing stress concentrations, or it might signal the onset of stable sliding before stick-slip.

Wesson and Ellsworth (1973) found periods of increased seismicity ranging in length from several months to years that may correspond to the period we observed 230 sec before slip. A pattern similar to the "peak and dip" pattern we report here was observed prior to the 1971 San Fernando earthquake (Ishida and Kanamori, 1977). Between 1961 and 1965 there was a period of increased seismicity within a 13-km radius of the eventual epicenter. This was followed by a period of no detected activity, lasting until 1969. For the remaining 2 years until the earthquake, activity in this region was relatively high. Other occurrences of this pattern of seismicity have been found preceeding earthquakes near San Juan Bautista, Stone Canyon, and San Benito in the San Francisco Bay area (Chuck Bufe, written communication, 1977).

In any case, we have observed that acoustic emission rate, or seismicity, and b-value both change before slip, suggesting that they may be used to predict earthquakes. Similar changes have been found in the field. Wyss and Lee (1973) observed decreases in *b*-value before several earthquakes in California. In addition, Chinese seismologists recorded an increase in seismicity and in the relative number of large earthquakes that occurred before the Haicheng earthquake, which they successfully predicted (Raleigh *et al.,* 1977).

The principle difficulty with this method of predicting earthquakes is the scarcity of events. Perhaps this problem could be alleviated by monitoring acoustic emissions in the field. In a well-bore in Stone Canyon near the San Andreas fault, Don Stierman (personal communication, 1977) observed signals that appear to be acoustic emissions generated by microseismic events in the surrounding rock. These signals, recorded with geophones at a depth of 300 meters, have a frequency in the low audio range and occur on a time scale of seconds or minutes. If these are in fact acoustic emissions from the rock around the well, they could be monitored for changes in *b*-values and emission rate.

In our experiment, it is remarkable that only one type of behavior was observed. Subsequently, we performed experiments in which water or oil was injected onto the fault surface. Due to equipment difficulties, the acoustic emission data were not recorded; however, we were still able to follow the emission rate, and several types of behavior were observed, including slip events of varying stress drop, with and without foreshocks and aftershocks, and swarms exhibiting no particular instability on the fault surface. This variety of behavior makes an experiment with water on the fault a high priority project.

In any case, we have shown that, in laboratory experiments, it is possible to predict slip on fault surfaces in dry rock. We have done this by monitoring acoustic emission rate and *b*-value of microseismic events. If the same effects are occurring in the field, they could be used as part of an earthquake prediction program.

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Manuscript received July 20, 1977