Contributions
to Current Research
in Geophysics (CCRG)
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Rock Friction and Earthquake Prediction

Editors:
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Editors' Note

Friction is one of the central problems for the understanding of earthquake source mechanism and earthquake preparatory processes. Active faults are clearly zones of weaknesses in the crust. On the other hand, some laboratory tests at high pressure indicate that the frictional strength of faults approaches the fracture strength of intact rocks. Therefore some of the major questions are: How is friction along fault planes overcome? Are the local shear stresses high, or could water and clay minerals act as weakening agents? The answers to these questions are fundamental to the proper design of laboratory experiments on precursory changes of rock properties.

A conference on 'Experimental studies of rock friction with application to earthquake prediction' was held at Stanford University on April 28, 29, 30, 1977. The conference was sponsored by the Office of Earthquake Research, U.S. Geological Survey, under the auspices of the National Earthquake Hazards Reduction Program.

The purpose of the conference was to gather together a number of experimentalists from North America who were actively working in the field of rock friction to discuss their progress and to discuss what seemed to be the most productive directions for further research. In addition, an attempt was made to synthesize the existing data and to discuss their significance for earthquake prediction.

The conference was designed around a series of invited papers that were either reviews of selected topics or were reports of original work. The benefits of the discussion at the conference were incorporated into many of the original papers, which were then submitted for publication in this volume. Additional papers were solicited from other workers to give a more thorough treatment and coverage of the subject.

One of the remarkable results of the experimental studies that were discussed in a number of papers is that, under high pressure, friction is almost independent of rock type, temperature, sliding rate, the presence of water, and the character of the sliding surfaces. These experimental results suggest that, under crustal conditions, the stress required to cause sliding of one rock over another is several kilobars. Measurements of the stress drop during even very large earthquakes is rarely greater than 100 bars so that, if the laboratory results are applicable to the natural situation, the stress drop would represent only a small fraction of the total shear stress. If, however, the shear stress is high, a very large amount of energy would be released during even very small earthquakes. The absence of any appreciable heat flow anomalies along active faults such as the San Andreas suggests either that the shear stress is low, which would be in disagreement with the laboratory measurements of friction, or that the energy is dissipated in other forms such as seismic energy, new surface energy, mineralogical phase changes or other as yet unidentified energy sinks.

A number of papers in this volume describe experiments that were designed to measure the temperature increase during frictional sliding, but, unfortunately, no successful attempt has yet been made to measure how the energy is partitioned between the various forms.

The results from a number of investigations in recent years have indicated that there may be an appreciable premonitory change in the seismic velocity through the epicentral region of large earthquakes. The conclusions drawn from this work have been questioned because it appears to be difficult to find travel time anomalies in California. Since travel time delays appear to be very small, care must be taken that data inhomogeneities and any systematic late picking of the first arrivals are not the actual cause of the quoted anomalies. A number of papers in this volume report the results of experiments that were designed to investigate how the seismic velocities change before fracture and frictional sliding. Although further work is required to investigate fully how velocity changes under all conditions of stress, pressure, temperature and pore pressure, the present data do indicate that the stress dependence of velocity is small. The stress change expected before even very large earthquakes may not be sufficient to cause velocity changes measurable with the techniques currently in use.

Other anomalous changes in physical properties that have been reported to occur before large earthquakes, such as electrical resistivity, magnetic susceptibility, premonitory slip and gas emission, have been investigated in the laboratory, and the results of these experiments are discussed in this volume.

The hypothesis that dilatancy occurs in the crust is fundamental to many theories developed to explain the anomalous changes that are purported to occur before earthquakes. In some models the diffusion of fluid through rock before fracture plays a critical role. This volume contains reports of the recent laboratory work that has been carried out to investigate the changes in dilatancy and permeability during changes in stress on rock.

A number of papers address the question of why in some situations a fault can slide stably, whereas in other situations it may slide jerkily. While it is still not always clear what physical mechanisms are responsible for the instability, it is generally accepted that the stiffness of the loading system, the variation of friction with displacement, and the time dependence of friction are important. The subject of transient creep in rocks, which seems to involve brittle fracture, fracture surface energy, and the effect of water on the strength of rock, is discussed in detail in a number of papers.

A number of papers both theoretical and experimental discuss particle and rupture velocity, radiation of seismic waves, and modes of slip during fracture and frictional sliding. Finally, two papers report field studies of the structure of natural faults and fault gouge, and one paper discusses in depth the mineralogical composition of naturally occurring gouge.

We have not attempted to make this volume a comprehensive treatment of all questions pertaining to rock friction and earthquake prediction. Subjects on which there exists a fair amount of information are treated more thoroughly than some problems which may be important but poorly explored. We hope that this mixture of review and research articles will be of interest and stimulate further research in this important field.

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A Review of Rock Mechanics Studies in the United States Pertinent to Earthquake Prediction

By J. Byerlee

Abstract – Premonitory phenomena such as dilatancy, creep, acoustic emission, and changes in seismic velocity and attenuation, electrical resistivity, magnetic moment, and gas emission, which occur before fracture of initially intact rock and before stick-slip on faults or between finely ground surfaces of rock, have been reviewed and discussed in relation to earthquake prediction. This review is restricted to the results of laboratory experiments that have been carried out in the United States of America.

Key words: Rock mechanics; Earthquake prediction.

Introduction

It is generally accepted that crustal earthquakes are caused either by sudden failure of initially intact rocks or by sudden stick-slip motion on pre-existing faults. These phenomena may be related if stick-slip is caused by sudden failure of the interlocked irregularities on the sliding surfaces [1].

In the past ten years considerable effort has gone into studying stick-slip and stable sliding in the laboratory. Much of this effort has been directed towards understanding earthquake source mechanisms [2, 3, 4, 5, 6]. It has also been hoped that if we knew exactly what physical conditions were necessary for stable sliding to occur, then we might be able to work out a scheme for controlling earthquakes by converting the unstable sections of natural faults into stable ones. However, I will focus on phenomena premonitory to earthquakes and not on the general subject of earthquake mechanisms or earthquake control. Even though an understanding of the earthquake process should ultimately be relevant to earthquake prediction, I will concentrate here on the laboratory results that can be clearly identified with premonitory phenomena.

Volume changes

The work of Brace *et al.* [7] shows that dense igneous rocks increase in volume before fracture. This phenomenon occurs even at pressures as high as 20 kbars [8] and at temperatures of at least 400°C [9]. The dilatancy in dense rocks such as granite is due to microscopic cracks induced by stress [10]. On removal of the stress, some of the cracks close but reopen when the stress is reapplied [11, 12, 13, 14]. Thus some of the dilatancy is reversible, and such reversal would be expected to occur in active tectonic regions where the rocks are subjected to many cycles of stress increase and decrease.

It has been shown that dilatant strain during deformation is anisotropic [15, 16, 17], and this should be taken into account when interpreting tilt data and velocity anomalies.

With highly porous rocks or loosely consolidated material the situation is more complicated. Both compaction and dilatancy occur together, and there may be a net decrease in the pore volume at the point of failure [18, 19, 20].

During direct shear, joints dilate before slip [21, 22], and even after many stick-slip cycles a small amount of dilation is observed before each event [23, 24], Fig. 1. In

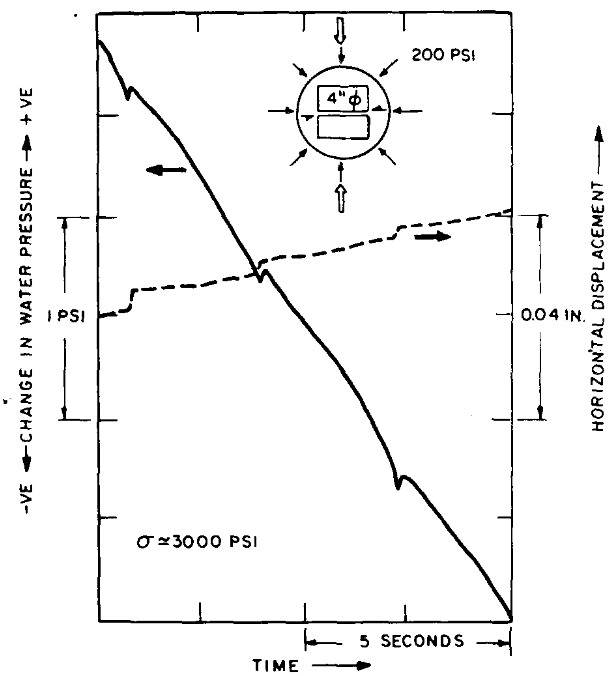

Figure 1
Water pressure-time relationship during stick-slip.

studies of sliding using samples with fractures, joints, or sawcuts, the dilation probably occurs at the sliding interface, and it has been found that during sliding between fracture surfaces the amount of dilation depends on the stiffness normal to the sliding surfaces [25].

HADLEY [26] has shown that at low pressure the stress required to initiate cracking in intact granite and gabbro exceeds that required to cause sliding on faults in the material, but to date no experiments have been carried out to study the volume changes in the fault gouge and in the intact rock during stick-slip at high pressure.

Permeability

Fluid flows through rock through interconnected pores and cracks. Under confining pressure these channels become constricted and the permeability decreases [27, 28]. A number of physical properties of rock depend not simply on the confining pressure but the effective pressure, that is, the confining pressure minus the pore pressure. This dependence on effective stress is true for permeability in dense igneous rocks such as granite [27], but not in rocks such as sandstone if the grains are surrounded by a layer of alteration products that have a compressibility different from the solid matrix [28].

Under confining pressure, with increasing differential stress the permeability of granite increases as the rock dilates, and near failure the permeability is 3 to 4 times its value under confining pressure alone [29].

The permeability of granite has been measured during the flow of water through the rock under confining pressure, differential stress, and temperature to 400°C. Because of the large variation in permeability among experiments carried out under the same conditions, it is difficult to evaluate the relation to stress or temperature, but the results show clearly that the permeability of granite decreases rapidly with time and, in some cases, particularly at the higher temperatures, measurable flow of water through the rock falls to zero. The minerals in the rock go into solution where the pressure is highest and deposit when the water becomes oversaturated as the water pressure decreases. These deposits clog the narrow pores and passageways so that the permeability is lower [30].

With loosely consolidated materials such as sand and crushed granite, the permeability decreases by a factor of 100 as the material compacts during deformation. At the peak stress these materials start to dilate, but the permeability continues to decrease although at a lesser rate [18, 19], Fig. 2. Under differential stress the permeability of these materials is anisotropic, being significantly lower in the direction of maximum compression than normal to that direction.

The permeability of a block of granite containing joints was measured, as stress up to 120 bars was applied parallel and normal to the joints. When the stress was normal to the joints the permeability decreased, but even at the highest pressure the permeability of the rock containing joints was at least a factor of 10^3 higher than the intact rock [31].

To date no experimental work has been carried out to determine the permeability of both country rock and gouge during repeated cycles of stick-slip at high pressure. This data is required to fully evaluate the dilatancy diffusion hypothesis for earthquake precursors.

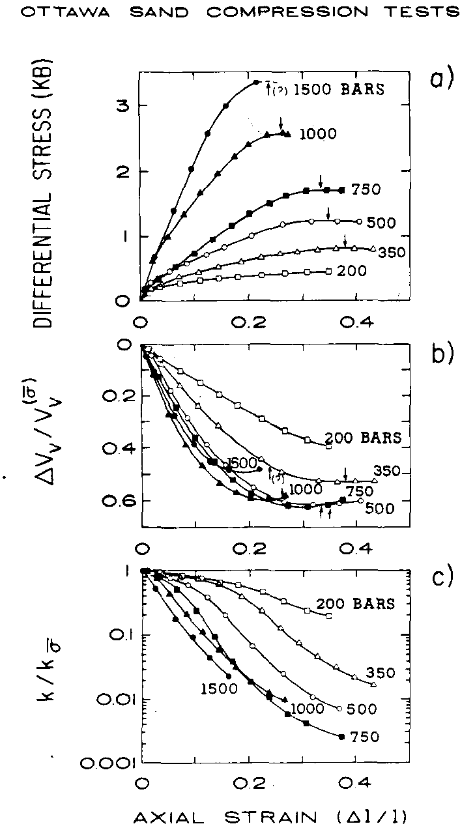

Figure 2
Deformation and fluid behavior of Ottawa sand in triaxial compression. Effective confining pressure for each curve is shown: (a) differential stress axial strain curve; (b) pore-volume strain as function of axial strain; (c) permeability in the direction of maximum compressive stress (normalized by permeability under hydrostatic conditions) as function of axial strain for these samples $K^{(200)} = 3.71$, $K^{(350)} = 3.98$, $K^{(500)} = 4.04$, $K^{(750)} = 0.80$, $K^{(1,000)} = 0.99$, and $K^{(1,500)} = 0.44$ darcys.

Creep

It has been shown that the frictional strength of rock is almost independent of rock type, and the stress required to cause slip at crustal pressures is several kilobars [32]. Analysis of seismic data indicates that the stress drop during even very large earthquakes is rarely greater than 100 bars [33]. Thus if the shear stress on a fault is high and the stress drops are low, then the fault is subjected to almost constant stress.

If an initially intact rock is subjected to these same conditions in a laboratory experiment, the rock deforms. Initially the 'primary' creep rate is high, but it eventually falls to a constant 'secondary' creep rate, and finally the 'tertiary' creep rate accelerates until catastrophic failure occurs.

At the low temperatures likely to be encountered in the crust the deformation of the rock during creep is probably time-dependent cracking [34, 35]. This time-dependent cracking under constant stress occurs with most brittle materials and is commonly called static fatigue [36, 37, 38, 39]. It has been suggested that static fatigue on a large scale may also be the mechanism of time-dependent phenomena observed for earthquakes [37].

With loosely consolidated material such as sand, time-dependent compaction occurs under pressure, and this is caused by time-dependent crushing of the grains [18]. During the deformation of granular materials there are two competing processes, compaction and dilatancy, occurring at the same time. At low pressure, equilibrium is reached when compaction and dilatancy are equal, and the material deforms without a change in volume. In that case no catastrophic failure occurs. At high pressure the material first compacts and, just before failure, dilatancy becomes predominant. A cursory effort has been made to study the effect of time on the strength of pre-compacted aggregates. In this case the material is weaker at the slower strain rates [40]. A systematic study, however, is required to determine the change with time of compaction and dilatancy of particulate material under high confining pressure, under both constant stress and constant strain rate conditions.

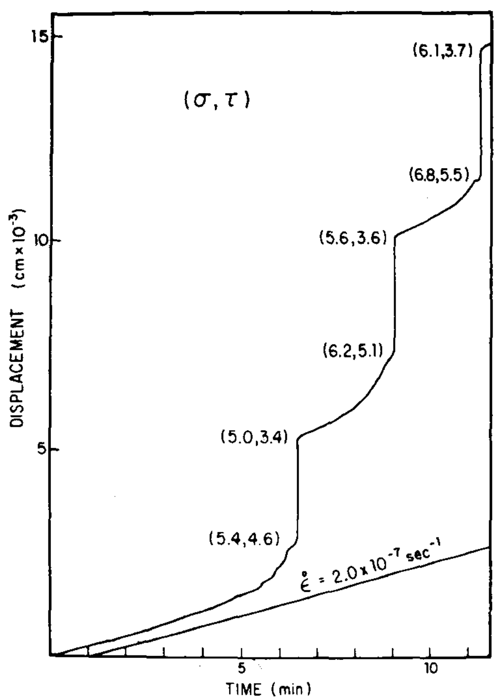

Figure 3
Sliding displacement versus time, showing details of episodic transition from stable sliding to stick-slip (large jumps in curve). Lower line indicates contribution to displacement data of elastic strain between LVDT mounts.

Some experiments have been carried out to study the time dependence of frictional strength of rock [41, 42, 43, 44, 45]. At low pressure the frictional strength increases with the time of stationary contact provided that the sliding surfaces are separated by fault gouge [41]. A detailed study of sliding between surfaces of granite at low pressure showed that the initial application of shear stress produced a displacement which continued at a decaying rate until sliding ceased. If the stress is increased the same thing occurs again; at still higher stress the creep rate decays but continues at a very slow rate; finally, the movement accelerates until catastrophic stick-slip occurs [43]. Thus during frictional sliding the three stages, 'primary,' 'secondary,' and 'tertiary' creep occur, and the same thing may be expected to occur in the natural situation as well.

In experiments with constant strain rate, a small amount of stable sliding occurs before sudden slip [42, 46, 47], Fig. 3. This preseismic slip always seems to occur, but the distance of sliding before slip decreases with an increase in confining pressure [47]. During stable sliding the gouge becomes crushed, and shear zones oblique to the sliding direction develop in the gouge. During sudden slip the movement seems to be confined to the interface between gouge and country rock [47, 48]. It has been suggested that if this occurs in the natural stituation, the slip plane for the foreshocks would have a different orientation from the main shock. There is some evidence to suggest that this may happen before some earthquakes [48].

Seismic Velocities

The velocity of P and S waves increases with pressure [49, 50] because under pressure, pre-existing cracks in the rock close and the elastic moduli are increased. If, however, the cracks are filled with water, the P-wave velocity at low pressure is much higher than when the rock is dry. At low pressure the shear-wave velocity is not affected very much by the presence of water [51]. Under differential stress rocks dilate before failure [7]; this dilatancy is caused by the development of new cracks within the rock. These observations led NUR [52] to suggest that, under stress, the ratio V_p/V_s should decrease if the rock becomes dilatant, and then increase again if water flows into the cracks from the surrounding regions. This dilatancy-diffusion model has been used to explain the V_p/V_s anomalies that are sometimes observed before large earthquakes [53].

It has been shown experimentally that a decrease in V_p/V_s occurs during the deformation of dry rock [60, 61] and an increase in the ratio occurs during the deformation of a fluid-saturated rock [54, 55]. But to date no reversal in V_p/V_s has been observed in any deformation experiments with fluid-saturated rock [54, 55].

The velocity of seismic waves through rock depends on both the ray path and the orientation of the polarization of the shear waves with respect to the principal stress directions [57, 58, 59, 60]. It has been suggested that similar anisotrophy in seismic velocities may precede earthquakes [58, 61].

It has been found that no velocity anomalies occur during frictional sliding between ground surfaces of granite [62], but when the sliding surfaces are separated by a large thickness of gouge a large decrease in velocity occurs before slip [63].

It has been found that during the deformation of pyrophyllite, both V_p and V_s first increase and then decrease as the material becomes dilatant, and finally the velocities decrease again during the formation of a fault. This phenomenon only occurred at very slow strain rates, and it has been suggested the same thing may occur with rocks like granite if the experiments are carried out slowly enough [60].

In experiments carried out to study the acoustic emission in rock it was found that apparent velocity anomalies occurred before failure of intact rock and before violent stick-slip in samples containing saw-cuts. Further analysis revealed that these fluctuations in calculated velocities were not due to changes in true seismic velocity but were shown to be related to sampling errors in picking first arrivals. The systematic picking of late first arrivals for small amplitude events was found to be a persistent bias resulting in low calculated velocities [64], Fig. 4. It was suggested that the seismic velocity anomalies that are sometimes observed before large earthquakes may be the result of a similar bias.

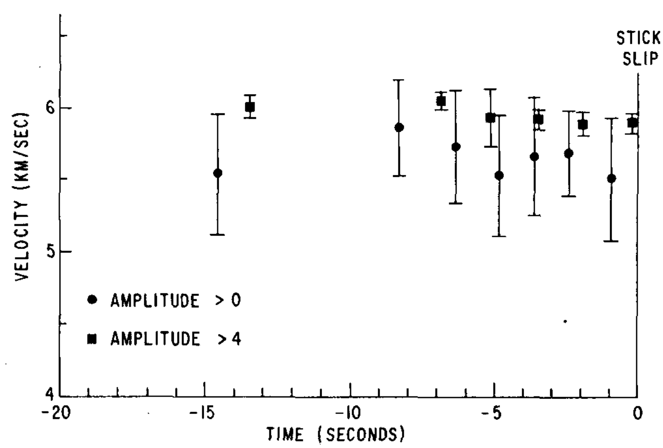

Figure 4
Average of calculated velocites for microseisms occurring before a violent stick-slip event. Averages of events of all amplitudes ●; average of events that had an amplitude greater than 4 on all stations ■. Error bar is standard deviation.

Seismic Attenuation

It has been found that the attenuation of the seismic waves changes during the deformation of rock [64, 65]. With some of the phases the attenuation increases, while with other phases the attenuation decreases [64], Fig. 5. It has been suggested [64]

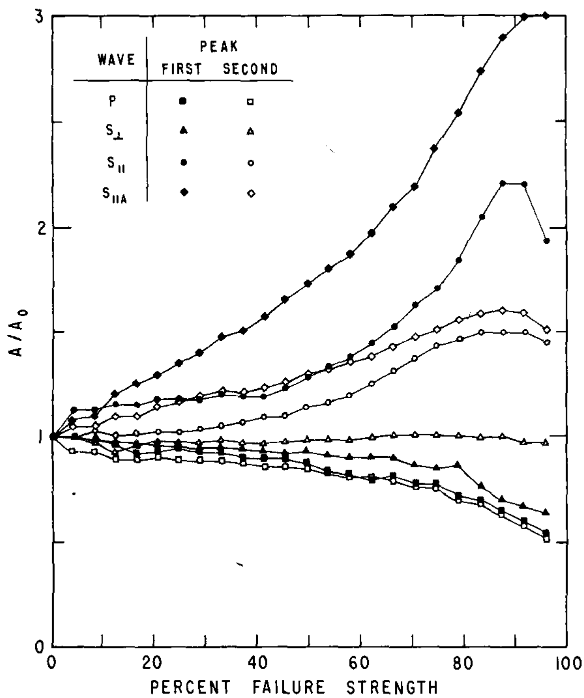

Figure 5
Amplitude ratios for first and second peaks of P, $S_\perp$, S_{II}, and S_{IIA} waves. A is the amplitude of the appropriate peak at hydrostatic pressure. The propagation of the waves was in the direction of the minimum principal stress. I and II refer to polarization directions perpendicular and parallel to the direction of the maximum principal stress.

that a similar anisotrophy in attenuation may occur in the natural situation and could be used as a warning of an impending earthquake.

Acoustic Emission

When a rock is stressed to failure, cracking on a microscopic scale occurs, and this cracking can be detected by monitoring the elastic radiation that is emitted by each event. This microseismic activity is known as acoustic emission and is considered by many to be simply a scale model of seismicity in the earth. Starting in the late 1930's acoustic emission has been used to predict rock bursts in deep mines [66]. An excellent review of the laboratory and field investigations of acoustic emission, oriented towards application in the mining industry, is given by HARDY [67].

There is a strong correlation between the amount of nonelastic strain and the number of acoustic emission events [68, 69]. It is generally found that as the rock approaches fracture the acoustic emission rate increases [68, 69, 70, 71, 72], although some workers have detected a slight decrease in activity just before failure [73, 74].

The acoustic emission activity sometimes increases before sudden stick-slip between ground surfaces of granite [77], Fig. 6. In other cases, however, it remains almost constant with little indication of any acceleration of activity before slip [78]. Similar results were obtained in frictional sliding experiments at temperatures as high as 700°C, although it is found that the acoustic emission rate decreases as the temperature is increased [79].

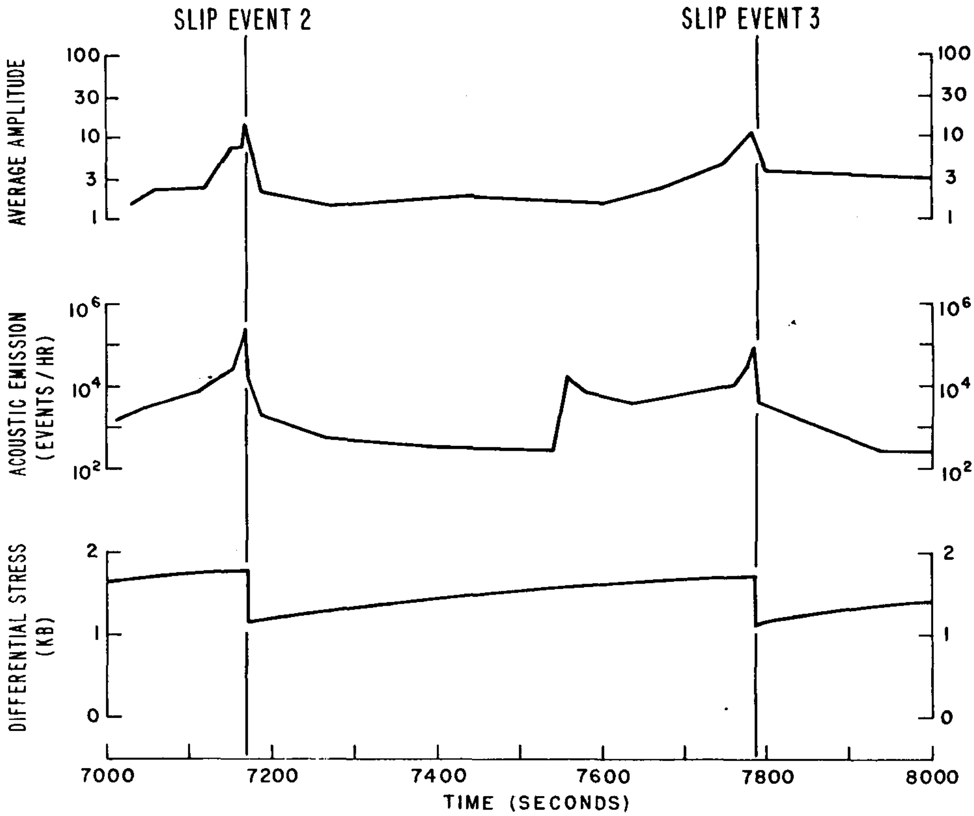

Figure 6
Parameters measured during the experiment are plotted for a time period including two stick-slip events. All values except differential stress, which was recorded continuously, are averages of measurements made for individual microseismic events.

SCHOLZ [70] found a clustering of the events on the eventual fault plane just before failure and suggested that spatial clustering of foreshocks may indicate an impending earthquake. Others, however, have reported that under some conditions no clustering of the events could be detected [75, 76].

The *b* value in the Gutenberg–Richter frequency-magnitude relationship increases with stress during deformation of initially intact rock [78], and the *b* value seems to