Changes in Seismic Velocity and Attenuation During Deformation of Granite

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The seismic velocity and attenuation were measured for P, $S_\perp$, and $S_\parallel$ waves traveling through a sample of Westerley Granite as it was deformed to failure under a confining pressure of 500 bars. All waves traveled in a direction normal to the axis of maximum compression, with $S_\parallel$ polarized parallel to the axis and $S_\perp$ polarized normal to it. By the time failure occurred, all seismic velocities had decreased by 12–30%. Amplitudes of the $S_\perp$ and P waves decreased by approximately 30%. A remarkable result of the experiment is that the amplitude of the $S_\parallel$ wave increased throughout the experiment until near failure. The amplitude at 90% failure strength was more than twice the value under hydrostatic pressure alone. These results are explained by analyzing how elastic moduli and energy dissipation due to frictional sliding at cracks are affected by anisotropic crack distribution developed in the sample as axial stress is applied.

INTRODUCTION

The effects of stress on seismic velocities in dry rock at temperatures and pressures simulating shallow crustal conditions have been studied extensively. At the same time the mechanisms responsible for attenuation are less well understood. The scarcity of data related to attenuation is due primarily to the fact that it is difficult to interpret records from either laboratory or field measurements. *Adams and Williamson* [1923] were apparently the first to report that the elastic modulus of rock increases when the hydrostatic pressure on the exterior of the sample is increased. Their explanation, which is now generally accepted, is that the increase in modulus is produced by closing of the cracks found in most crystalline rock. Cracks are also thought to be a source of the dissipation that causes seismic attenuation in rock at relatively low temperature and pressure [*Orowan*, 1934; *Born*, 1941; *Walsh*, 1966; *White*, 1966]. One of the mechanisms proposed for attenuation involves friction. By this model a wave propagating through the sample forces the sides of a crack to slide in relation to one another. The energy required to do this comes from the acoustic wave and is dissipated as heat. As a result the wave is attenuated. *Birch and Bancroft* [1938], in one of the few experiments of this sort, showed that attenuation of shear waves decreased by an order of magnitude in granite when hydrostatic pressure acting on the sample was increased from 0.2 kbar to 4 kbars. According to this model, increasing the confining pressure closed cracks and increased friction, so that no slip could occur. As a result, dissipation decreased.

The effect of the nonhydrostatic component of stress on propagation characteristics is a topic of practical importance. It has been suggested that observations of changes in seismic velocities could indicate that failure of the rock is imminent, thereby providing a way to predict both rock bursts in mines and earthquakes on faults [*Tocher*, 1957]. For example, *Nur* [1972] and *Scholz et al.* [1973] have suggested that before some large earthquakes the ratio of the seismic velocities V_p/V_s is anomalously low. Although the change in seismic velocity that accompanies dilatancy in initially intact rock is small (of the order of 10% in a test to failure [*Tocher*, 1957; *Gupta*, 1973; *Bonner*, 1974; *Hadley*, 1975], in principle it is possible to measure such changes in the earth. Unfortunately, the volume of rock undergoing such a change usually is small in relation to the path length. Consequently, measurements of the seismic velocities across active tectonic regions by different methods may yield different results [*Whitcomb*, 1973; *Kanamori*, 1975].

Attenuation is a measure of the nonelastic components of deformation and may therefore be more sensitive than velocity to defects in the medium through which the wave propagates. One would expect a large change in attenuation to accompany the microfracturing that occurs before a sample fails. For confined experiments in which the applied stress was other than hydrostatic, however, no measurements of attenuation have been reported. It is of interest to study attenuation under confined conditions, since this duplicates more closely the conditions found in the earth's crust. Many of the open cracks which contribute to wave attenuation in unconfined experiments will be closed when the sample is confined.

Absolute measurements of attenuation are difficult to make. The signal depends in part upon the coupling between the transducer and the sample, and small changes in the coupling can lead to large changes in the output of the transducers. In the experiments that we are reporting, we avoided this problem by keeping the confining pressure and the amplitude of the excitation pulse constant throughout the experiment. The only parameter that was varied in this experiment was the magnitude of the axial stress. The signal of the receiver is affected by spreading of the transmitted wave as well as by losses between the tranducers and the sample. Here, we are interested in relative changes in attenuation produced by stress, rather than in the absolute value of attenuation. For this reason we determined only how the amplitude of the wave at the receiver changed as the sample deformed. In an effort to account for possible changes in wave form brought about by changes in velocity and attenuation we measured changes in the ampli-

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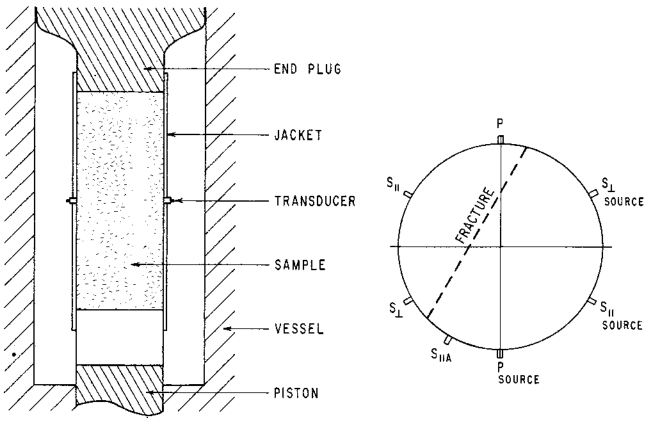

Fig. 1. Schematic view of sample mounted in pressure vessel and cross section of sample showing location of transducers and trace of fracture surface.

tudes of the first three peaks of the S waves and the first two peaks of the P waves.

EXPERIMENTAL METHOD

A cylindrical sample of Westerly Granite, 19.05 cm long by 7.62 cm in diameter, was jacketed in a polyurethane sleeve to seal it from the confining fluid. The sample was mounted in a pressure vessel (described by *Byerlee and Lockner* [1977]), and confining pressure of 500 ± 5 bars was applied. The pressure was held constant throughout the experiment by means of a servo-controlled pump and drain. The axial load was increased in steps of 276 bars by advancing a piston, actuated by a hydraulic ram, against the end of the sample. Failure occurred at 6.62-kbar differential stress.

Seven piezoelectric transducers, mounted on steel plugs, were epoxied to the surface of the rock. The transducers, which had a resonant frequency of 600 kHz, were arranged in a plane perpendicular to the axis and located midway between the two ends of the sample, as shown in Figure 1. The orientation of $S_{\parallel}$, in our convention, is parallel to the axis of the sample, that is, in the direction of maximum compression. Note the additional shear wave receiver referred to as $S_{\parallel A}$ mounted 90° from the $S_{\parallel}$ source transducer. This receiver was included to determine whether variations in amplitude depended on the radiation angle from the source.

At each stress level a square wave pulse of 12 V was applied to the source compressional wave transducer. Velocities and amplitudes of the first two peaks of the P wave and the first three peaks of the $S_{\parallel}$ and $S_{\perp}$ waves were measured at each level of stress. The signal from the receiver compressional wave transducer, mounted on the sample directly opposite the source transducer, was amplified and fed into a time delay oscilloscope. The delay time between the source and receiver signals was measured to ±0.2-μs accuracy. Amplitudes of the peaks in the receiver signal were measured to approximately 1% accuracy. After the P wave amplitudes were measured, the source signal was successively applied to the $S_{\parallel}$ and $S_{\perp}$ source transducers.

All arrival time delays were measured at the first zero crossing of the receiver signals. This procedure introduces a systematic error of about 1 μs, but it assures a much smaller relative error between measurements than could be obtained by measuring the first arrival of the wave. A low-amplitude P arrival that preceded the S arrival could be seen on the shear wave records. This contamination was a result either of mode conversion at the steel-rock interface at the source transducer or of production of some compressional wave mode vibration by the shear wave transducers. These unwanted P wave arrivals were of such low amplitude that they did not affect the measurement of the shear wave amplitude by more than a few percent.

The pulse generator (HP model 214A) was regulated to produce a 12-V square wave pulse of 40-μs duration every 4200 μs. The 4200-μs delay was chosen to assure that all reflections in the sample had damped out before the next pulse arrived. The 40-μs pulse width was chosen to allow each acoustic wave to reach the receiving transducer before the source transducer was turned off, thereby assuring no contamination of the first arrivals of the receiver signals.

Although the transducers had a resonant frequency of 600 kHz, the receiver signal was about 300 kHz as a result of resonance in the steel plugs attached to the transducers. Because of this, only the first peaks in the wave train were used to measure attenuation of the acoustic waves as they traveled through the sample. The shape of these first peaks was stable throughout the experiment.

A number of effects in addition to the intrinsic attenuation in the rock can contribute to changes in the amplitude measured at the receiver transducer. Losses in the acoustic signal due to scattering are difficult to estimate. As cracks open in the sample, scattering is expected to increase, since the wavelengths used in these experiments are of the order of a centimeter. We have no estimate of the importance of the change in scattering as the sample approaches failure.

Another loss of energy in the acoustic signal occurs at the steel-rock interface, where part of the wave is reflected, owing to the acoustic impedance mismatch between the two materials. Since the impedance of a material is a function of its acoustic velocity, the impedance of the rock changes as it approaches failure. This would result in a change in the amount of energy transmitted across the rock-steel interface. Another effect is the focusing of the beam caused by the curvature of the rock-steel interface. Because of the geometry of the experiment and the fact that all velocities decrease above about 30% failure strength, increasing differential stress tends to focus all three types of acoustic waves. This conclusion was arrived at by constructing refracted ray paths from the source transducers. First-order calculations for beam focusing and impedance mismatch for our experimental setup show that these two processes are of the same magnitude and tend to cancel out. Consequently, they should contribute an error of a

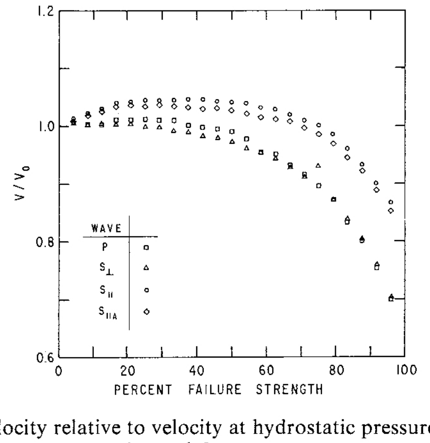

Fig. 2. Velocity relative to velocity at hydrostatic pressure for P, $S_{\perp}$, $S_{\parallel}$, and $S_{\parallel A}$ waves.

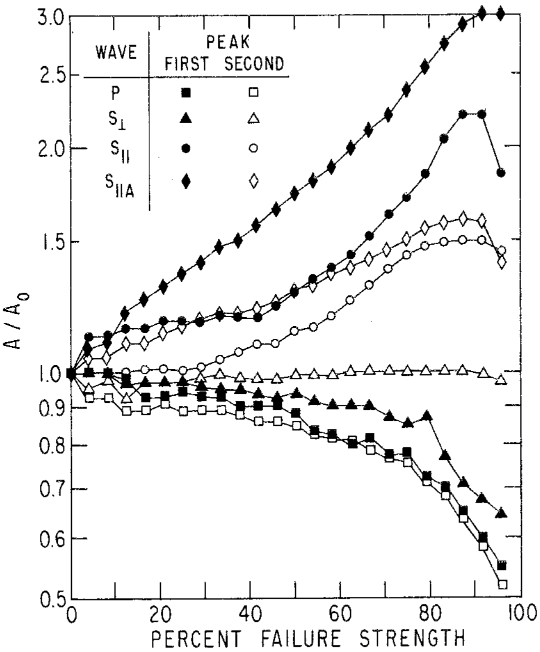

Fig. 3. Amplitude ratios for first and second peaks of P, $S_\perp$, $S_\parallel$, and $S_{\parallel A}$ waves as a function of failure strength. A_0 is the amplitude of the appropriate peak at hydrostatic pressure.

few percent to the amplitude measurements. Mode conversion of P and S waves at the rock-steel interface also will change as the sample approaches failure. Errors due to this factor are insignificant.

Discussion

The effect of axial stress on shear and compressional velocities observed in our experiments (Figure 2) is about the same as that observed in previous experiments [*Tocher*, 1957; *Hadley*, 1975; *Bonner*, 1974]. We see in Figure 2 that velocities at low axial stress levels are relatively insensitive to increases in axial stress, whereas velocities at high stress levels decrease at an increasing rate with increasing axial stress. These characteristics are generally thought to be produced by cracks, both those which are present in the unstressed samples and those which are introduced by the applied stress. Consider the effect of axial stress on the crack population. Increasing axial stress closes cracks normal to the axis of the sample (horizontal cracks in our experiment). Vertical cracks are unaffected by axial stress until the stress is greater than approximately one third to two thirds of the ultimate strength. Cracks throughout the sample begin to grow at these higher stress levels in such a way that the elongation of existing cracks and the orientation of new ones are found to be predominately parallel to the axis of compression. As a result the sample becomes increasingly anisotropic, the compliance parallel to the axis continually decreasing and the compliance normal to the axis increasing at stresses above the level at which cracks begin to grow. Finally, at axial stresses near the ultimate strength, crack growth becomes localized, a fault forms, and the specimen fractures.

Let us confine our attention to behavior at stresses below the stress at which the fault forms (i.e., stresses less than about 90% of the ultimate strength); we assume for simplicity that the axial stress affects only vertical and horizontal cracks, changing their concentrations, as was described above. We find that the changes in crack distribution produced by axial stress affect the propagation of the P waves and the $S_\perp$ and $S_\parallel$ waves in somewhat different ways. Note that $S_\perp$ waves and P waves propagating normal to the axis of compression, as in this experiment, are influenced by changes in the population of vertical cracks but not by changes in the population of horizontal cracks. Therefore, as shown in Figure 2, P and $S_\perp$ velocities remain approximately constant as horizontal cracks close and decrease as vertical cracks increase in number at stresses above one third of the ultimate strength, whereas velocity in the $S_\parallel$ mode is influenced by both horizontal and vertical cracks. The $S_\parallel$ velocities in Figure 2 therefore first increase with increasing stress as horizontal cracks close, then decrease as the number of vertical cracks increases.

The results of the amplitude measurements provide a critical insight into the mechanism by which waves are attenuated in dry rock at relatively low pressure and temperature. Under these conditions, attenuation in rock samples as characterized by the specific quality factor Q is found to be independent of frequency over a very wide range (for a summary, see *Knopoff* [1964]). This characteristic suggests that dry friction, where dissipation does not depend upon sliding velocity, causes the attenuation observed [e.g., *Born*, 1941]. The process we consider here was described by *Walsh* [1966]. We begin by assuming that stresses exerted by a wave are very small in comparison with applied stresses. Dissipation can occur only for those parts of the cracks where the faces are barely touching; stresses exerted by a wave are not sufficient to cause slip on cracks that are more tightly shut, and slip which occurs on open cracks does not result in dissipation. Attenuation is therefore produced primarily by those cracks oriented such that the maximum shear stress exerted by this wave is in the plane of the crack. This model suggests that horizontal cracks should not affect the attenuation of P waves and $S_\perp$ waves in our experiment, and, in fact, the amplitude of the P and S waves plotted in Figure 3 does not change appreciably at low applied stress levels where horizontal cracks are closing. The attenuation of $S_\parallel$ waves, however, should be affected by horizontal cracks. The number of sites on horizontal cracks where sliding can occur decreases as the axial stress is increased. We see in Figure 3 that the attenuation of $S_\parallel$ waves decreases with increasing stress at low levels of load, as the model suggests.

As was described above, the number of vertical cracks increases at higher load levels because of microfracturing. If attenuation occurs primarily on cracks oriented in the direction of maximum shear stress, attenuation of $S_\parallel$ waves due to

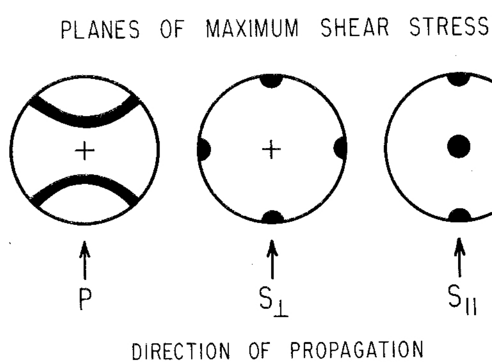

Fig. 4. Equal-area projection of poles of maximum shear planes caused by the passage of P, $S_\perp$, and $S_\parallel$ waves. The direction of wave propagation is indicated by the arrows. The axis of the sample is located at the center of each plot. The poles of vertical cracks would fall along the rim, whereas horizontal cracks would be located at the center of each plot.

vertical cracks is caused by dissipation at crack surfaces that are normal to the direction of propagation. On the other hand, attenuation of the $S_\perp$ waves is caused by dissipation at two sets of vertical crack surfaces, those that are normal to the direction of propagation and those that are parallel to the direction of propagation. This effect is demonstrated in Figure 4, in which equal area projections are shown of the poles of planes of maximum shear stress that result from the passage of P, $S_\perp$, and $S_\parallel$ waves. The axis of the sample would plot at the center of each projection. As shown by Figure 4, dissipation in the P wave mode also occurs primarily at two sets of vertical cracks, located symmetrically at about 45° to the direction of propagation. Therefore, increasing the number of vertical cracks is expected to result in a greater increase in attenuation for P waves and $S_\perp$ waves than for $S_\parallel$ waves. We see in Figure 3 that attenuation for P and $S_\perp$ modes increases at higher stresses, as one would expect. Attenuation for the $S_\parallel$ mode continually decreases until the sample is near the fracture point. This behavior is probably a result of a competition between the decrease in dissipation of the $S_\parallel$ wave due to horizontal crack closure and the increase due to vertical cracking. The effect of crack closure apparently dominates until the applied load is nearly at the fracture strength. Both granite and sandstone samples have been studied, and in both cases this effect occurred.

One feature of Figure 3 for which we have no good explanation is the high attenuation along the $S_\parallel$ path relative to that along the $S_{\parallel A}$ path. Consideration of the effects of spreading of the wave suggests that the amplitude ratio for $S_{\parallel A}$ should be lower, not higher, than that for $S_\parallel$ at the same stress level. Possibly, mode conversion at the receiver sites causes unforeseen effects, or, possibly, increased diffraction of the wave at higher stress affects the $S_\parallel$ (which has a longer path length) more than the $S_{\parallel A}$. In any event, the feature that our discussion hinges on is that attenuation decreases with increasing axial stress in the $S_\parallel$ mode but not in the $S_\perp$ or P modes; both $S_\parallel$ curves have this characteristic.

The differences in attenuation for the various modes were quite unexpected. A decrease in velocity is generally accompanied by an increase in attenuation and is associated with an increase in the number of cracks. The results in Figure 3 show that this rule of thumb is not always valid. A number of models have been proposed to explain the relationship between velocity and attenuation in dry rock at these relatively low pressures and temperatures. These models should now be reexamined in the light of these new data.

As dissipation occurs in response to the component of shear displacement in the plane of the crack, we expect that the attenuation of shear waves of any polarization propagating along the axis of our sample will decrease as compression closes cracks. Since we are unable to propagate waves along the axis of the sample with the present apparatus, we cannot check this hypothesis directly. *Merkulova et al.* [1972], using a resonance technique, measured the velocity and attenuation of compressional waves propagating parallel to the axis as a function of axial stresses as high as 1 kbar. Compressional wave velocities in quartzite and granite were found to increase with increasing compression, but attenuation remained constant until the load exceeded about 500 bars. Such behavior follows from the mechanism we propose here: Axial compression closes cracks and causes velocity to increase. Attenuation does not increase at low stress levels, however, because the horizontal cracks that are closed do not contribute to the attenuation of compressional waves directed along the axis. Attenuation begins to decrease only when stresses are sufficient to close the cracks at higher angles to the axis, angles that do contribute to dissipation. *Rao and Ramana* [1976], however, report attenuation decreasing in uniaxial tests at very low stress. This may reflect a difference in rock types used.

Little has been done to look for changes in attenuation in the field. For foreshocks occurring in a localized region about a large earthquake, changes in the ratio of the amplitudes of P and S waves might be attributed primarily to two causes: Relative amplitudes for P and S waves following a given ray path would be sensitive to changes in the orientation of the fault plane as well as to changes in the relative attenuation of the waves. If fault plane solutions could be determined accurately enough, effects due to changes in the radiation pattern could be compensated for, and changes in attenuation might be determined. In practice, this would require a well-placed and extensive network of seismic stations. *Mantis and Lindh* [1976] have compared small amplitude foreshocks and aftershocks of the Oroville earthquake of August 1975. They report changes in the amplitude ratio of P and S waves between the foreshocks and aftershocks. If suitable records on foreshocks are not available, an alternative method might be to detonate explosive charges and measure amplitudes of waves traveling through the stressed regions.

The most critical result of this experiment is that an unexpected change in seismic attenuation was observed in laboratory tests. If the same effect occurs in the field, it should be observable. If this were the case, measurement of changes in seismic attenuation could prove to be a valuable earthquake predictor.

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