Reports

Velocity Anomalies in Dilatant Rock

Abstract. *Seismic velocities measured in rock deformed in the laboratory show excellent agreement with theoretical predictions of the effects of crack growth during dilatancy. Under appropriate conditions dilatancy was observed to produce a drop in the ratio of the seismic compressional velocity to the seismic shear velocity both by the mechanism of undersaturation and by a liquid-gas phase transition.*

Velocity anomalies have been observed to precede a number of earthquakes (*1*) and have been interpreted as resulting from preearthquake dilatancy (*2*). Experimental results (*3*) showed that anomalies in the ratio of the seismic compressional velocity to the seismic shear velocity (V_p/V_s) can be produced in the laboratory but are small in amplitude. Here we compare the experimental results (*3*) with theory (*4*) and show that the data are in excellent agreement with theoretical expectations and that there is no theoretical or experimental reason why much larger velocity anomalies may not be observed under appropriate conditions.

The data we discuss have been presented before (*3*). Values of V_p and V_s were measured in rock cycled in compressive loading at a confining pressure of 390 bars. Figure 1 shows these data superimposed on theoretical curves of O'Connell and Budiansky (*4*). In Fig. 1 $\bar{V}_p$ and $\bar{V}_s$ are the observed velocities and V_p and V_s the intrinsic velocities of the rock. Figure 1, a to c, is for a cracked solid with a water-air mixture in the cracks. The solid curves in Fig. 1a are loci of constant saturation fraction ξ and the dotted curves loci of constant crack density ϵ.

The data in Fig. 1, a and b, are for Westerly granite. The closed symbols indicate data taken during loading and the open symbols data taken during unloading. The data taken at the peak stress achieved during the cycle are indicated by a number that gives the peak stress in kilobars (for instance, 1.75 and 1.98 in Fig. 1a). The circles in Fig. 1a are for a drained experiment at a pore pressure (P_P) of 350 bars (water) cycled at a strain rate of 10^{-6} sec^{-1}. By drained, it is meant that the sample was connected to a large reservoir of fluid maintained at the pore pressure. The sample has a fluid diffusion time constant of only 2 minutes (*3*), so under these test conditions we should not expect the sample to become undersaturated. At the initiation of loading the velocities lay on the saturated curve at the point marked *O*. As loading proceeded, the velocities first fell to the origin along the saturated curve, indicating crack closure; then as dilatancy began to occur they moved up and to the right along the saturated curve, showing excellent agreement with theory and indicating an increase of crack density with stress under saturated conditions. The velocities did not initially change on unloading, suggesting frictional locking of cracks (*5*), but after the load had been reduced by 1 kbar, they began to fall back down along the saturated curve to final values very close to the initial values.

Velocities for a "dry" rock (squares in Fig. 1a) began near the origin, and as loading progressed $\bar{V}_p/\bar{V}_s$ first rose, then fell rapidly to approach the dry curve at the peak load. This rock was exposed to air at laboratory humidity for several days before the test, and these data suggest that it contained enough adsorbed water to act saturated at first, then rapidly became undersaturated as dilatancy proceeded. Considerable hysteresis was observed during unloading. This is expected because in this experiment a large amount (1×10^{-3}) of permanent dilatancy was produced (*3*).

An undrained test at $P_P = 350$ bars (water) is shown in Fig. 1b. In this test the sample was isolated from the reservoir and the pore pressure allowed to vary in response to dilatancy. The velocities were initially near the origin, and as loading proceeded they moved out along the saturated curve, as in the drained case. However, unlike the drained case, the velocities continued to move out along the curve during the initial period of unloading, indicating increasing crack density (the velocity path during unloading is indicated by arrows). There must have been a substantial pore pressure gradient in this sample, since at peak load the pore pressure (measured external to the sample) had fallen to 307 bars, and the velocities (measured near the center of the sample) indicate dilatancy hardening, since they indicate much lower crack densities at peak stress than in the drained case with the same sample (Fig. 1a), even though the peak stress was higher. Furthermore, the dilatancy measured with strain gauges in the undrained case was only about 60 percent of that in the drained case at peak stress. We therefore interpret the increase of crack density during unloading indicated by the velocities as being due to dilatancy induced by pore fluid flow into the dilatancy-hardened central section of the sample (dilatancy softening).

San Marcos gabbro is much less permeable than Westerly granite—it has a diffusion time constant of 80 minutes (*3*). It is thus possible that this rock will exhibit undersaturation under the available test conditions. The results for several experiments in which this rock was initially saturated with water at a pore pressure of 1 bar are given in Fig. 1c. In the drained test at a rate of 10^{-6} sec^{-1}, $\bar{V}_s$ continually decreased with stress, but this was accompanied by only a very slight rise in $\bar{V}_p/\bar{V}_s$. These data departed markedly from the saturated curve, indicating progressive undersaturation as dilatancy occurred. The tests at higher rates, both drained and vented to the atmosphere, showed more pronounced undersaturation, as would be expected, and were sufficient to reduce $\bar{V}_p/\bar{V}_s$ by several percent.

Several experiments were conducted with CO_2 as the pore fluid to see if a liquid-gas phase transition, which occurs in CO_2 at 62 bars, could be induced by dilatancy. The results of these tests, conducted with Westerly granite drained at $P_P = 112$ and 62 bars and a rate of 10^{-5} sec^{-1}, are shown in Fig. 1d. Since CO_2, both as a gas and as a liquid, possesses elastic constants intermediate between those of water and air, we cannot use the limiting theoretical case as we did for water and air. The results for CO_2 will be sensitive to a parameter

$$\omega = \frac{a}{c}\,\frac{\bar{K}}{K}$$

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where c/a is the crack aspect ratio, $\tilde{K}$ the bulk modulus of the fluid filling the cracks, and K the bulk modulus of the rock. Scanning electron microscope (SEM) studies of these rocks after straining showed that most cracks had an aspect ratio of $c/a \geq 10^{-3}$ (3). Using appropriate values for $\tilde{K}$ and K (6), we obtained the bounding values for CO_2 fluid-saturated (at 100 bars) and gas-saturated (at 50 bars) cracks with $c/a = 10^{-3}$ given as dashed curves in Fig. 1d. Since most of the data for the experiment at $P_P = 112$ bars significantly exceeded the upper bound, it is concluded that the aspect ratios of cracks under the experimental conditions were considerably smaller than those of cracks observed under the SEM, probably due to closure under the effective confining pressure of several hundred bars. A value of $c/a = 10^{-4}$ was found to be in best agreement with these data (solid curves in Fig. 1d).

In the test at $P_P = 112$ bars the velocities were initially near the origin, and as load increased $\bar{V}_P/\bar{V}_S$ rose, paralleling the predicted liquid curve. At a stress of 2.75 kbar, however, $\bar{V}_P/\bar{V}_S$ began to fall, indicating that the pore pressure had dropped to 62 bars and the phase transition was taking place. This drop continued with increasing crack density but the transition was not complete at peak stress. In the test conducted at the transition pressure, $\bar{V}_P/\bar{V}_S$ fell throughout the experiment, indicating that the phase transition began as soon as dilatancy commenced. The velocities at peak stress are given by the first star in Fig. 1d. At that point the CO_2 was vented to the atmosphere to ensure that the phase transition did take place. The velocities after venting are given by the second star. They do not differ significantly from the velocities before venting, showing that the transition had already gone to completion. These final values agree quite closely with those predicted by the theory (solid curve for the gas). Although the reduction of $\bar{V}_P/\bar{V}_S$ was only 3 percent in this experiment, it was exactly as theoretically predicted for a rock with CO_2-filled cracks of $c/a = 10^{-4}$.

These results show that experimental observations of dilatancy-induced velocity changes are quite consistent with theory, although there remains a quantitative disagreement between crack densities inferred from velocities by using the theory and those measured with SEM observations (7). Much of this discrepancy may be due to the strong anisotropy that appears to be inherent in dilatancy (8), which is not taken into account in the theory. These results also show that velocity changes are very sensitive to the scaling conditions: the ratio of fluid diffusion rate to dilatancy rate, the supply of pore fluids, the properties of the fluids, and the aspect ratio of fractures. Velocity anomalies (reductions in $\bar{V}_P/\bar{V}_S$) were produced both by dilatancy-induced undersaturation and by a phase transition. Although they were only several percent lower than the intrinsic velocities (note that the "dry" experiment in Fig. 1a can be considered an undersaturation case also, with a 6 percent anomaly), that is what is predicted by the theory for these experimental conditions. Since the theory permits much larger velocity anomalies, these results do not imply that much larger velocity anomalies cannot take place under other experimental conditions or in the earth.

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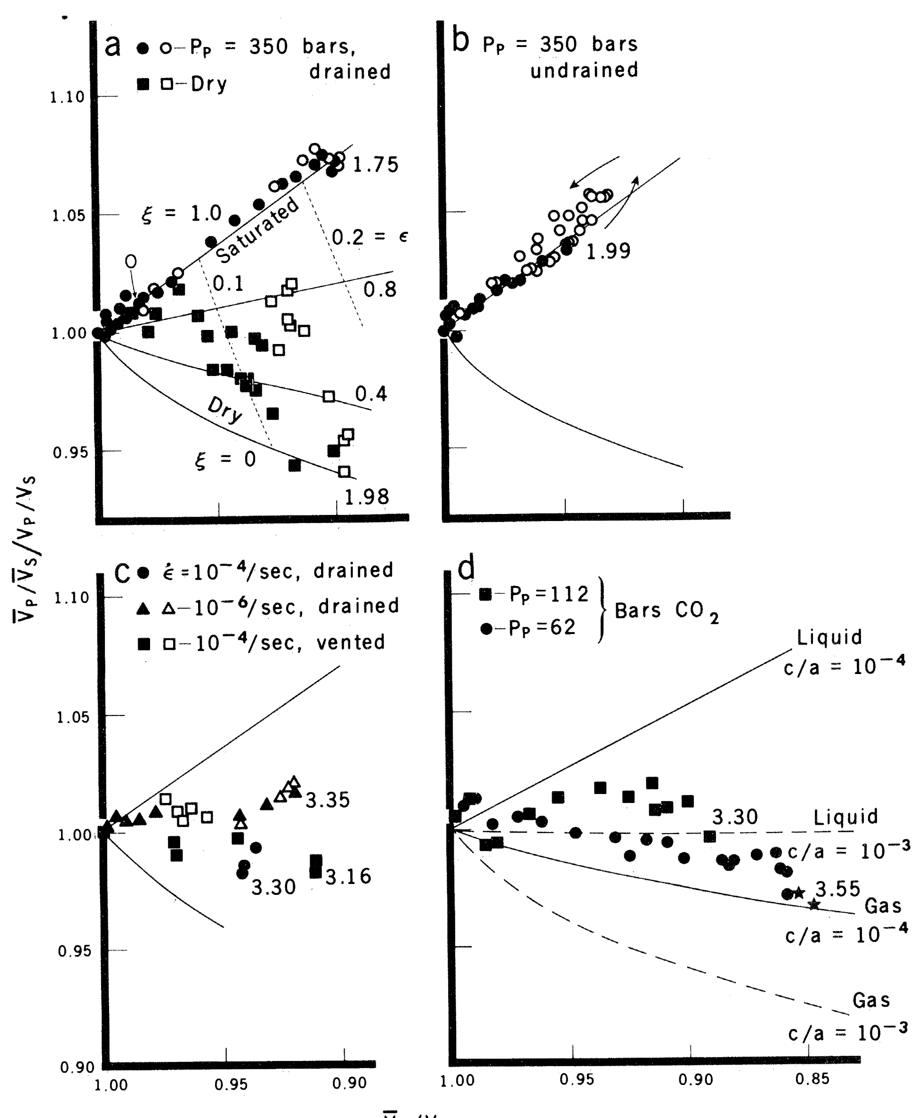

Fig. 1. Measurements of V_p and V_s made during cyclic loading of rock in compression (3) compared with theoretical predictions (4).

References and Notes

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