Seismic Velocities in Porous and Fissured Rocks

by

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Introduction

The rational basis for using seismic exploration methods consists of two steps. In the first step, we attempt to determine the velocity distribution in a crustal section from seismic data. In the second step, we attempt to obtain from the velocity the structural setting of the strata and the physical properties of their rocks. The first step received extensive attention over the years. Many exploration seismologists consider their task, out of habit, to find the velocity distribution. Some tend to forget the next step, going from velocity to actual material. This second step is just as important, and unfortunately also as difficult, as the first. It is important particularly when we are looking for non-structural reservoirs of oil, steam or water. Here we must determine whether the rock is porous, and if so what is contained in the pores. The difficulty arises from the fact that various combinations of rock types, porosity, pressure and fluid inclusions can yield identical velocities. It is therefore necessary to understand what determines the velocity of seismic waves in porous rocks.

Aside from velocities, there are two other features of waves which are useful in seismic exploration -- amplitudes and frequency content. The amplitude and frequency content of a seismic signal is modified by the intrinsic attenuation of the rock and the transmission and reflectivity of interfaces throughout the rock mass. We must therefore study also the nature of attenuation in rocks, as well as the factors which control the coefficients of transmission and reflection. The latter is strongly dependent on the acoustic impedance, which is in turn determined by the effective density and seismic velocities in the rock. Thus, discontinuities in velocity and density cause impedance discontinuities, which are responsible for strong reflections. These reflections have become a prominent tool -- the bright spot concept -- for the detection of shallow gas pockets. In geothermal areas it appears that the dominant effect on waves is that they are greatly attenuated, either due to scattering by inhomogeneities or by an intrinsic dissipation process. Furthermore, we know now that compressional and shear waves are affected in different ways by gas inclusion, by attenuation and by fluid inclusions.

The purpose of our study is thus to understand the variables and parameters which control wave propagation, and following this, to uncover ways of extracting more information from waves about the physical state of the composite rock through which they travel. In this report we concentrate on velocities.

Method

To study the velocity of seismic waves in rock we utilize the pulse transmission method. In this method an electrical pulse is transformed by a piezoelectric transducer into a mechanical pulse. The mechanical pulse travels along the sample, and is converted back into an electrical signal at a receiver transducer. The travel time is measured accurately as a function of confining stress or pressure p_c, pore pressure p_p, pore fluid, temperature and compaction history. We also measure the sample's length and porosity. The laboratory measurements are made with signals whose energy is in the 100 KHZ -- 2 MHZ band.

Confining pressure at room temperature is applied by hydraulic fluid, surrounding a copper jacketed sample, and argon at high temperature. Pore pressure is applied independently of confinement. The pore fluid is water or steam. Nonhydrostatic stress, when applied, is produced by solid compression. Heating under pressure is achieved in an internally heated pressure vessel. The pressure range of our experiments is from 1 to 7000 atmospheres, and the temperature ranges from 20°C to 500° or more.

Experimental Results: Effects of Stress, Fluids, Dilatancy Compaction and Temperature

In the past several years we investigated the effects of various parameters on wave velocities in rocks. The results to date are summarized in figures 1 to 7.

a. Stress Induced Anisotrophy:

As shown in figure 2 (dry case) increasing confining pressure in rocks increases both V_p and V_s velocities. This is caused by the closure of narrow microcracks under pressure. If we apply a nonhydrostatic confining stress we would expect to induce anisotropic crack closure distribution, leading to anisotropic velocity distribution. A good example is shown in figure 1, in which a sample of Westerly granite was loaded uniaxially (as shown in inset). We find that the p velocity and the velocity of one shear wave show relatively strong dependence on direction, whereas the second shear wave velocity is only slightly dependent on orientation (Nur and Simmons, 1969). These observations are in good agreement with

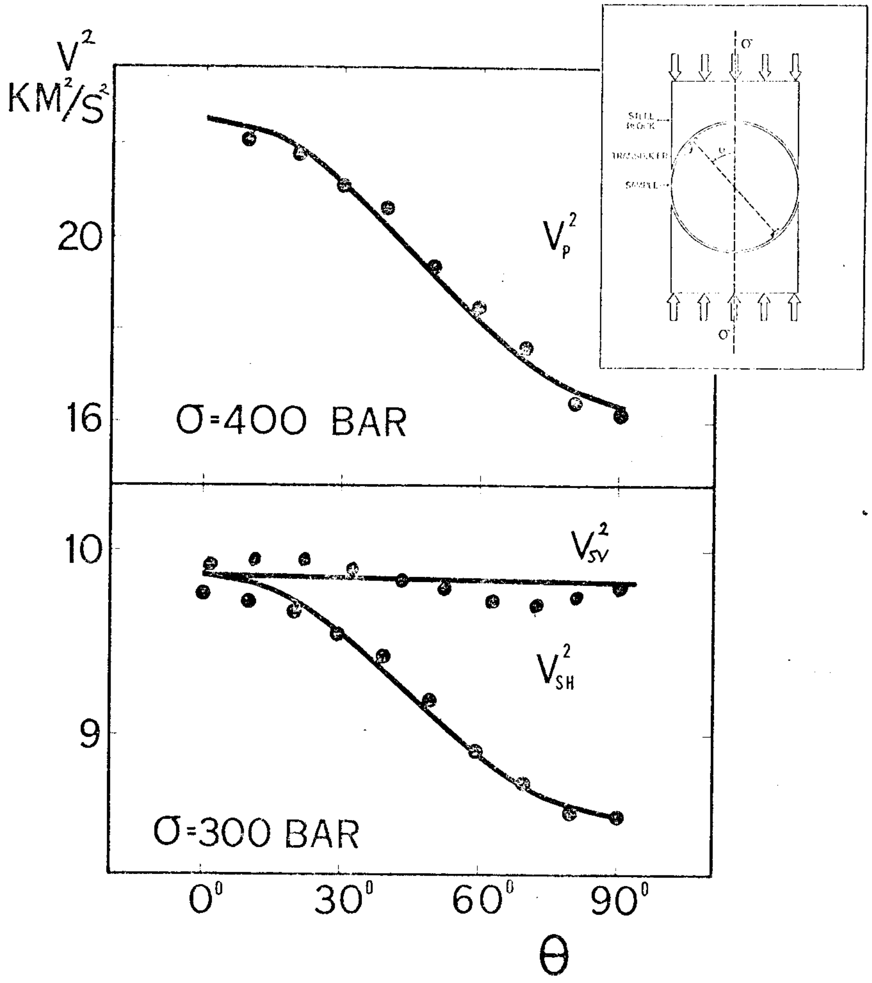

Fig. 1. Velocity anisotropy induced in Westerly granite by uniaxial stress.

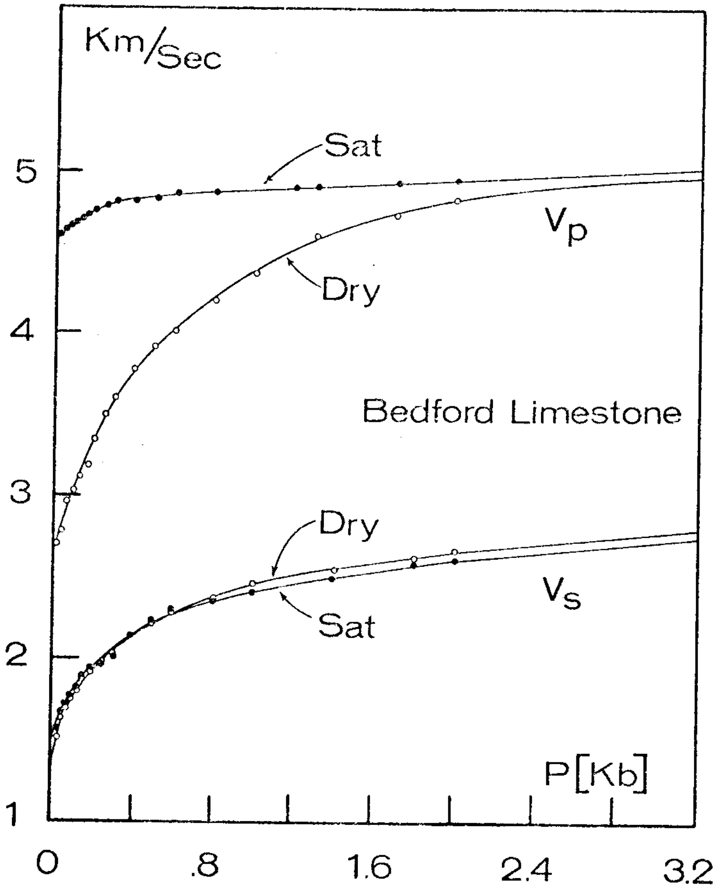

Fig. 2. Compressional and shear velocities in Indian sandstone (Bedford limestone) as a function of confining pressure and saturation. Pore pressure is kept at 1 Atmosphere.

theoretical calculations based on crack closure (Nur, 1971).

b. Saturation:

Figure 2 shows the effect of fluid saturation on V_p and V_s in Bedford limestone. As predicted by the Gassman equation, the compressional velocity is greatly increased by saturation, whereas, the shear velocity is only slightly affected. Similar results were obtained for several rock types with low porosity.

c. V_p/V_s Ratio and Dilatancy:

In order to remove the explicit dependence on pressure from the saturation effect we plot in figure 3 the ratio of V_p/V_s against V_p for three granites. In this space the effect of saturation is highlighted. Saturated points are in the upper region and dry values are in the lower regions. We compare these plots with the now well known insitu ratio changes preceding the San Fernando earthquake of 1971. It appears that one or two years before this earthquake the ratio decreased, indicating the appearance of dry or partially dry pore space. Following recovery, due to inflow of water or plastic crack closure, the region failed, producing a moderately strong earthquake.

d. Velocity and Compaction of Noncompetent Rock

Many rocks of interest are broken, fissured or granulated. In these rocks, confining pressure increases not only the velocity but also the density in an irreversible way. Figure 4 shows the changes induced in clean sand. Porosity has decreases by 25% during a compression cycle, due to extensive crushing, and shows a strong irreversible behavior. The velocity, in contrast, is approximately reversible with confining pressure. This means that the effect on velocity of the decrease in porosity is offset by the increase of the number of grains, or in other words, the increase in internal surface area (Talwani et al., 1973).

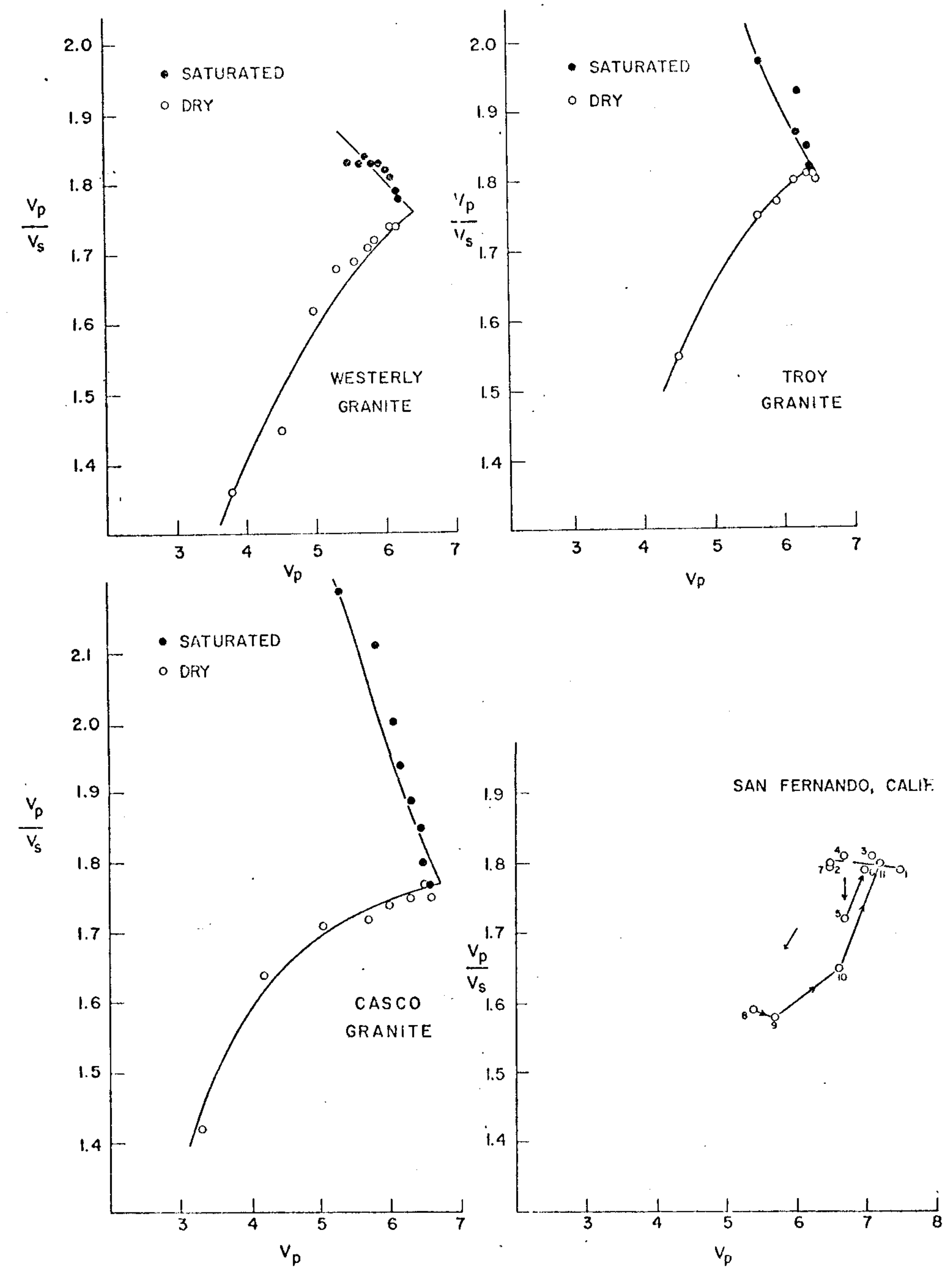

Fig. 3. The ratio V_p/V_s as a function of V_p for dry and saturated rocks. Insitu ratio preceding the San Fernando earthquake (1971) are also shown.

e. Temperature and Compaction:

Table 1 shows the permanent velocity increases induced by moderate heating of particulate samples. The effect is very significant even for short duration and low temperatures. Although as yet poorly understood, these results imply that processes other than mechanical may play a major role in determining velocities in situ.

TABLE 1

Compressional Velocity in Volcanic Ash Samples After Various P-T Cycling. Measurements at Room Conditions.

Pressure History	Temperature/time History	Compressional Velocity
2.5 kb	room temperature	.77 km/s
10.0 kb	room temperature	1.10 km/s
2.0 kb	200°C/ 1 hrs.	1.90 km/s
2.0 kb	300°C/ 5 hrs.	4.0 km/s

f. Effects of Temperature and Pressure

We have measured the compressional and shear velocities of crystalline rocks to temperatures over 400°C, while the sample is under 5 kilobars hydrostatic confining pressure (figure 5). Compressional velocities increase rapidly with increasing pressure below 2 kilobars, as the numerous microcracks in this sample are being closed. At higher pressures, in the more linear portion of the curve, the isotherms display the decrease in velocity as temperature increases. Temperature has a larger retarding effect on shear wave propagation, and the decrease in shear velocity is particularly large between 300 and 400°C.

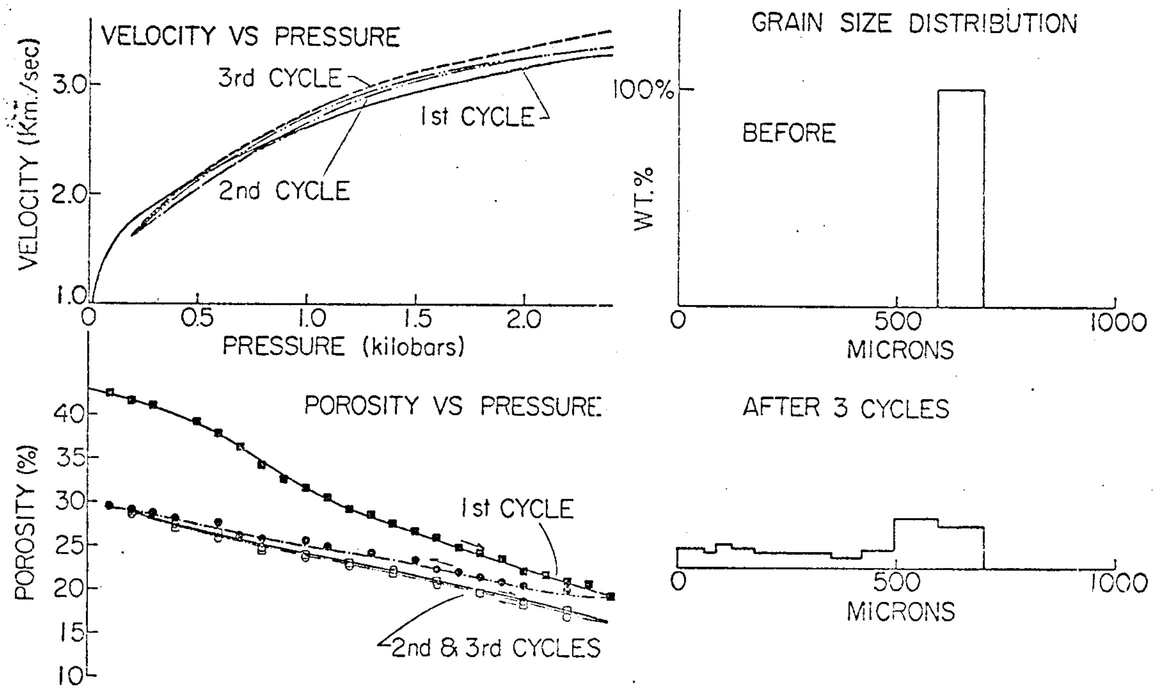

Fig. 4. Compaction and compressional velocity in a sand pack as a function of pressure cycling.

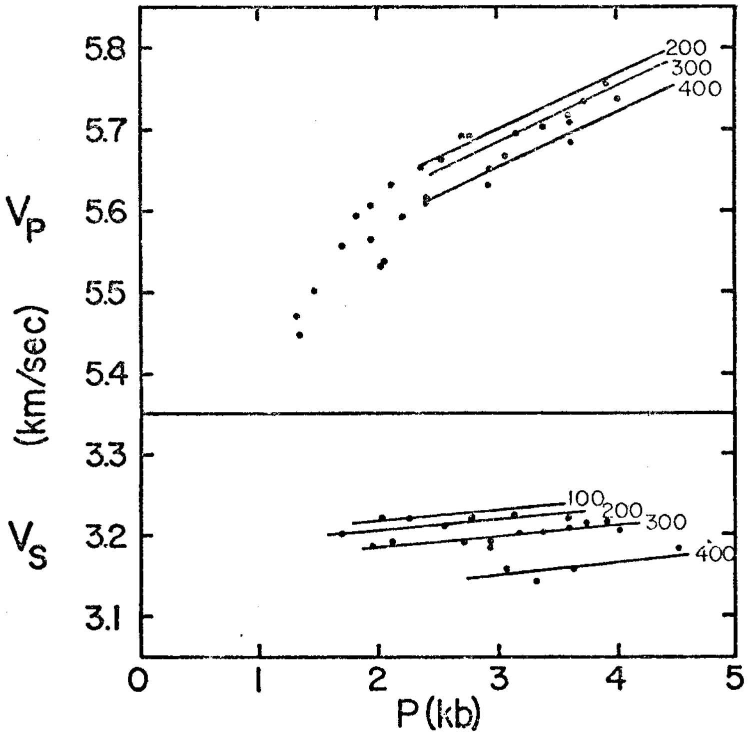

Fig. 5. Compressional and shear velocity in Westerly granite as a function of pressure and temperature.

The computed elastic moduli (figure 6) are somewhat lower than other published reports, and this is attributed to the microcracks which form during pressure-temperature cycling. The bulk moduli fall within the narrow shaded region, and there is no systematic temperature dependence. In contrast, the shear modulus decreases markedly with increasing temperature. The decrease in compressional velocity with increasing temperature, is therefore largely due to a decrease in the shear modulus whereas the bulk modulus is relatively unaffected.

The concurrent measurement of compressional and shear velocities permits calculation of Poisson's ratio, and its value is of interest because one normally assumes that the seismic ray parameter is constant within the crust and upper mantle. The results show that both temperature and pressure act to increase Poisson's ratio. Pressure acts primarily by increasing the bulk modulus, while temperature markedly decreases the shear modulus of the aggregate.

In separate experiments, we have independently controlled the pore-fluid pressure inside the jacketed sample. We are examining whether the physical properties of super-critical water might produce 1) seismic velocity inversions which have been tentatively identified in the earth's crust and 2) variations in V_p/V_s which are premonitory to some thrust-type earthquakes, and 3) velocity variations associated with hot water and steam geothermal areas.

Conclusion

We have recognized three types of parameters which determine the velocities in rocks:

(a) physical fields such as confining pressure, temperature, pore pressure;

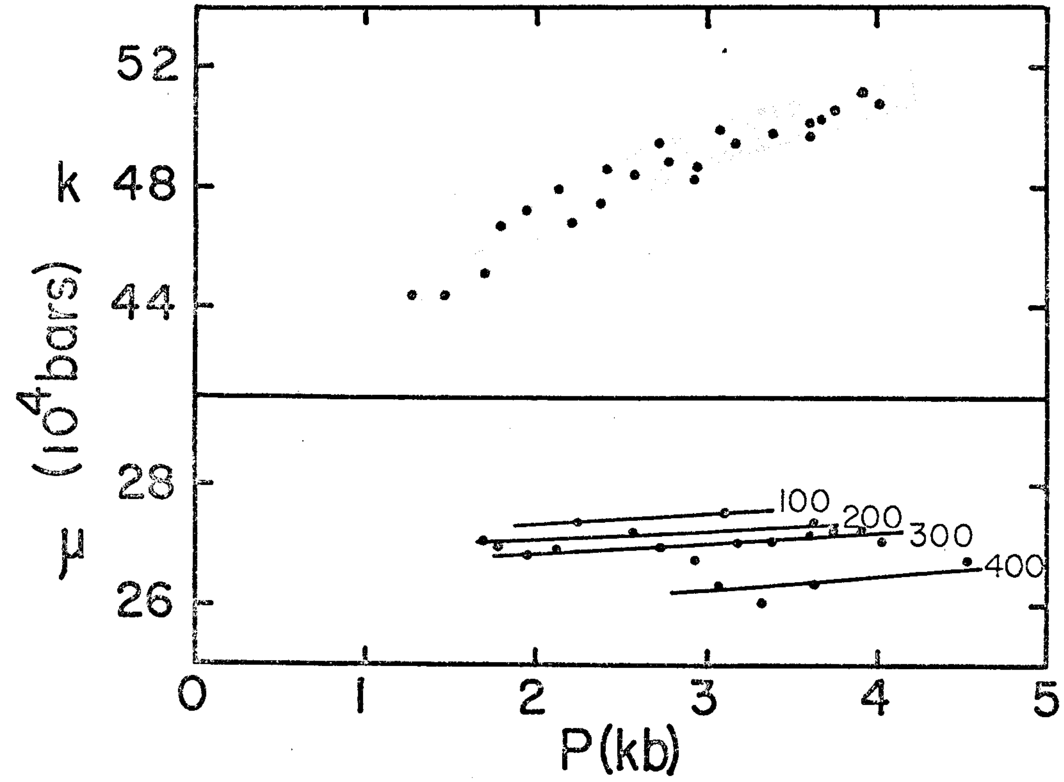

Fig. 6. Effective bulk and shear moduli of Westerly granite as a function of pressure and temperature.

(b) intrinsic material properties such as porosity, stiffnesses and permeability of rock, density and viscosity of fluid inclusion;

(c) interactions between solid and fluid phases, such as surface cohesion, rearrangement of fluid structures, chemical processes associated with compaction etc.

The effects of the first two groups of parameters are now reasonably well understood, at least in a qualitative sense. It is the third group which poses the main challenge. It appears that time dependent effects may be completely controlled by surface phenomena associated with a fluid phase in the pores. Of particular interest is the mechanism of seismic attenuation in rocks which has not as yet been identified. Preliminary results suggest that local fluid flow, absorbed on solid interfaces may be responsible.