Fluids and frequency dependent seismic velocity of rocks

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Summary

Compressional and shear velocities of rocks are dependent on frequency and this dispersion may be significant even within the seismic band. The amount and position of dispersion will be largely a function of fluid properties, distribution, and motion in the pores. Velocities are thus directly coupled to rock permeability and pore compliance. Propagation often will be in the high frequency regime, even at a few tens of Hertz. Static, or low frequency models such as Gasmann will fail under such conditions. In addition, Biot theory will not correctly model wave propagation in many cases.

Introduction

Seismic velocities are one of our most important geophysical parameters and tools. Velocity and density contrasts permit us to image reservoirs. Velocities can be used directly in such applications as in overpressure prediction. They can be used indirectly through their influence on reflection coefficients and amplitudes for purposes such as direct hydrocarbon indicators. Attempts are commonly made to predict velocity changes during recovery processes for reservoir monitoring. We need to have a complete understanding of how velocity behaves and relates to our objectives.

Considerable effort is expended reconciling velocity values made through surface seismic, cross-borehole, well log, and laboratory techniques. Even in a completely homogeneous rock, frequency dependent velocities, or dispersion, yields nonconstant values between different measurement bands. This dispersion is a complex function of pore fluid properties and mobility. As a result, with sufficient information, dispersion could itself be used as a fluid indicator or as a remote measurement of permeability.

Our research quantifies the possible levels of dispersion and relates these to rock and fluid properties. We have conducted velocity measurements over a broad frequency band ranging from below seismic to ultrasonic. Commonly used relationships and theories can be tested directly by manipulating fundamental fluid and rock properties such as viscosity and permeability.

Method

Compressional and shear velocities were measured using a combination of stress-strain and ultrasonic techniques. Samples were typically 2.54 cm in diameter and 5 cm long. High frequency (approximately 800 kHz) velocities were calculated from transit times using the standard pulse-transmission technique. Low frequency velocities (5 to 2500 Hz) were calculated from measured moduli using a stress-strain technique similar to that of Spencer (1981). This analysis assumes the rock is a homogeneous (non-porous), isotropic material so results might be considered ‘apparent’ velocities. Strain levels were maintained within the linear, seismic range between 10^{-8} to 10^{-6}.

Fluid flow across sample boundaries often corrupts low frequency laboratory data. To prevent unwanted boundary effects, we seal the outer cylinder surface with an impermeable coating. For high permeability samples, the pore fluid lines must also be closed during measurement (Yin, 1992).

Results - Viscosity influence

Fluid motion and pressure control rock velocity changes and seismic sensitivity to pore fluid types. One obvious factor is viscosity. The two most commonly used theoretical concepts are the inertial coupling of Biot (1956) and the ‘squirt’ flow mechanism (see, for example, O'Connell and Budiansky, 1977, or Divorkin and Nur, 1993). Biot gives a characteristic frequency, ω_c (roughly, the boundary between high and low range) with the viscosity dependence, η, in the numerator:

$$\omega_c = \eta\phi / k\,\rho.$$

Here ϕ is porosity, k is permeability, and ρ is fluid density. However, squirt-flow mechanisms lead to viscosity dependence in the denominator:

$$\omega_c = K\alpha^3 / \eta.$$

Here K is frame modulus and α is crack aspect ratio. These contrasting dependencies indicate viscosity can be an obvious test to ascertain which theory is applicable.

Fluids and frequency dependent seismic velocity

Figure 1 shows the strong dependence on temperature of glycerine viscosity. Other properties, such as bulk modulus, change as well, but not by the order of magnitude as does viscosity.

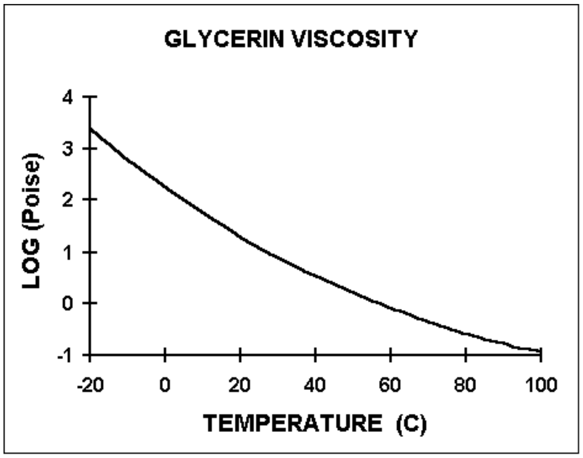


Figure 1. Glycerine viscosity as a function of temperature (after Viswarnath and Natarajan, 1989).

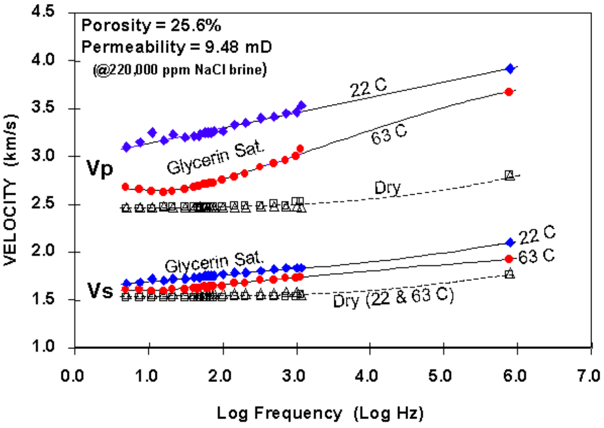


Figure 2. Compressional and shear velocity versus frequency for the dry (open symbols) and glycerine saturated (solid symbols) Upper Fox Hills Sandstone. Velocities were measured at 22 (blue) and 63 (red) degrees C at an effective pressure of 17.24 MPa.

Compressional (Vp) and shear (Vs) velocities for a sample of the Upper Fox Hills Sandstone (Heather well) are shown in Figure 2. Several features should be noted. For the dry sample (open symbols), Vp and Vs show little frequency or temperature influence. This confirms that the primary dispersive and temperature effects are dependent on pore fluids. When saturated with glycerine, strong temperature and frequency dependence is obvious. Shear velocity is not independent of the fluid, but increases with increasing fluid viscosity indicating a viscosity contribution to the shear modulus. Vp increases with viscosity also. More importantly, the dispersion curve shows a systematic shift to lower frequencies with increasing velocities, consistent with the model of squirt flow.

Results - Permeability influence

Rock permeability also strongly influences fluid motion and therefore fluid pressure and seismic velocity. In a manner similar to what we saw with increasing viscosity, lower permeabilities should require longer times, or lower frequencies, for saturated rocks to relax.

In a single rock sample, the permeability can be altered substantially by slightly modifying the pore texture. Clays such as smectites are sensitive to the pore fluid salinity. At high salinities, the clay structure is collapsed. At low salinities, water is absorbed and the clays expand. Thus we can modify the pore space and the permeability by altering fluid salinity. Figure 3 shows both the measured permeability with the schematic change in pore structure as salinity is modified. The process is reversible, and other physical properties such as density, viscosity, formation factor etc., do not change significantly with clay expansion.

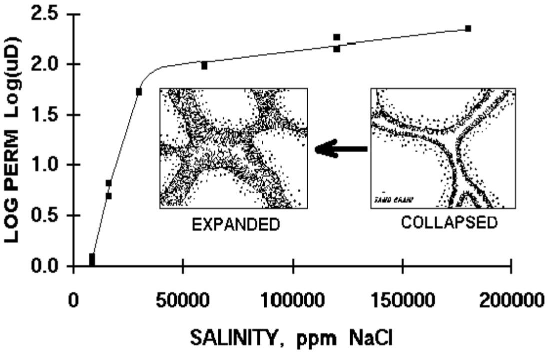
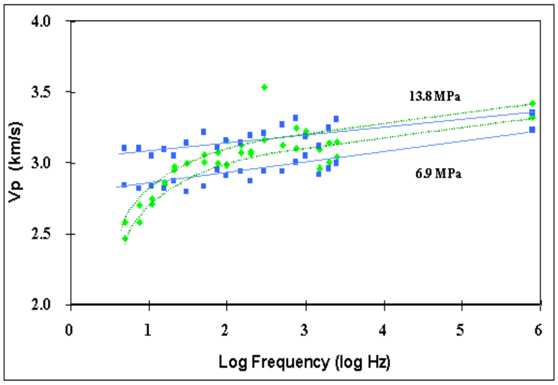


Figure 3. Measured permeability for sample YM5154 as a function of salinity. The behavior of the expanding clays with decreasing salinity is shown in the boxes. (Sketch is after Neasham, 1977)

Clay-rich sandstone sample YM5154 has a high smectite content. At high salinities and relatively high permeabilities, dispersion is strong and well within the seismic band (green points in Figure 4). Vp ranges from 2.5 km/s at 5 Hz to 3.0 km/s at 150 Hz. Velocity continues to increase more slowly to 3.4 km/s at megahertz frequencies. This dispersion occurs even at elevated pressures. The seismic velocities are not within the low frequency regime, nor do they agree with standard sonic values or those collected ultrasonically.

Figure 4. Compressional velocity versus frequency for the YM 5154 sandstone sample at two effective pressures.



Green diamonds are with the sample saturated with high salinity brine, blue squares are for the sample saturated with distilled water..

After fresh water is pushed through the sample, the clays swell and permeability drops by more than two orders of magnitude. Under these conditions, velocity dependence on frequency changes dramatically. As can be seen, ultrasonic velocities were little effected and Vp remained almost constant down through the seismic band. As far as this low permeability sample is concerned, seismic frequencies are not in the dispersive region and are equivalent to ultrasonic frequencies.

The generalized frequency dependence indicated by these results is shown in Figure 5. This Cole-Cole plot does not indicate any specific mechanism, but does permits us to plot velocities and associated attenuations over a very broad range assuming some simple, single relaxation distribution. Our measurement window is limited, as indicated by the dashed box. The effect of lowering permeability was to increase the relaxation time needed for fluid equilibration, thus lowering the dispersion frequency. Because of the causal relation of attenuation to velocity, we also expect the attenuation peak to drop in frequency.

Conclusions

Seismic velocity dispersion can be significant with resulting inconsistent velocities when compared to logging or laboratory values. In extreme unrelaxed cases, the seismic frequency band may be equivalent to ultrasonics. Low frequency 'static' porous media theories such as Gassmann will fail under such conditions.

The measured viscosity dependence is consistent with local or squirt flow theories. Biot's relation does not correctly model the observed dependence on pore fluid viscosity. Biot's theory is thus not appropriate under many conditions.

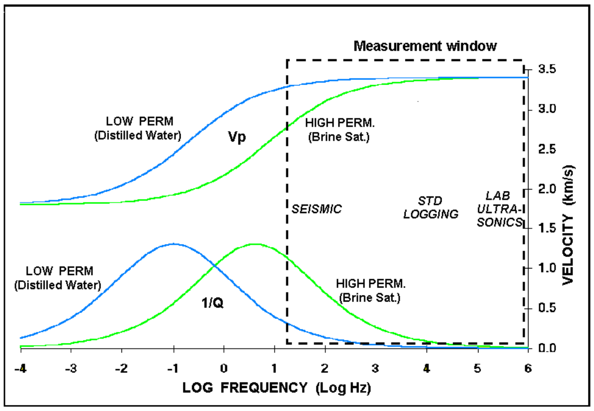


Figure 5. Cole-Cole type plot showing the general postulated downward shift in frequency as permeability decreases for both velocity and attenuation.

Acknowledgments

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