Macro-flow and Velocity Dispersion

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Summary

Deformation resulting from a compressional wave can cause pore fluid motion on the order of the wavelength. If the fluid mobility is high, pressure can be equilibrated between regions of gas versus brine saturation. This can result in a relaxed, drained velocity even lower than dry or gas saturated velocities. This diffusion of fluid pressure can cause a gas-water contact that looks sharp at high (logging) frequencies to be gradational at seismic frequencies. This fluid motion can also result in high attenuation.

Introduction

We have seen in several of our low frequency experiments, how fluid flow can influence the seismic velocities (Figure 1). Pore pressure changes slightly as a seismic wave passes, causing the rock to be slightly stiffer and increasing velocity. This pressure change depends on the compressibility of the fluid and the compliance of the pore space. This process is described by Gassmann's (1951) Equations. However, these equations were derived under the assumption that that pore pressure has equilibrated throughout the rock. This assumption then depends on fluid mobility. At low mobility, pressure can not equilibrate and Gassmann's assumptions are violated. With increasing mobility, 'squirt' flow mechanisms can operate over a small distance, and adjacent pores can reach equilibrium. With high mobility, a more global or 'Macro' flow can occur on a scale approaching to the seismic wavelength.

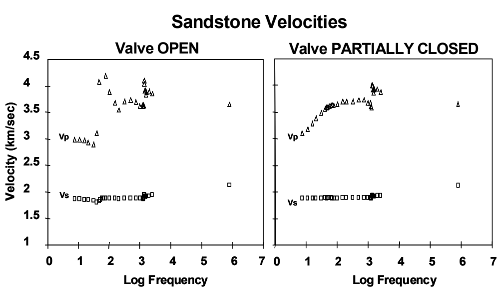

Figure 1. The influence of pore fluid flow in and out of sandstone. At high frequencies, flow cannot occur. At low frequencies, brine moves in and out of the pore fluid line. Note that shear velocity is not influenced.

This Macro-flow allows pressure equilibrium between regions saturated by different fluids. Thus, a completely brine-saturated portion of the rock can "see" or interact with an adjacent gas-saturated (or partially-saturated) zone. Although the details of the mechanism are not completely described, our low frequency data shows this phenomenon conclusively.

One of the most straight-forward descriptions was developed by Cole and Cole (1941) and applied to attenuation measurements by Spencer (1981). The result is coupled attenuation and velocity as functions of frequency as shown in Figure 2.

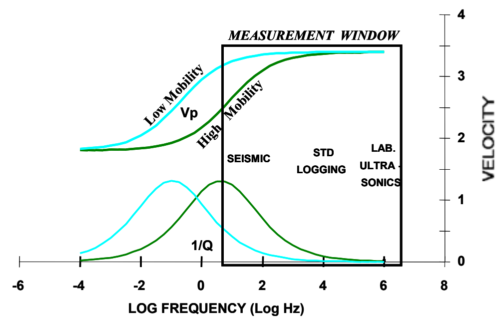

Figure 2. Cole-Cole relation couples velocity and attenuation as functions of frequency. The frequency range of our laboratory measurements is indicated. Also shown is the effect of high fluid mobility and low fluid mobility.

For diffusive fluid flow, the specific rexation time can be written as

$$\tau = C\frac{x^2}{K_f}\frac{\eta}{k} \quad . \qquad (1)$$

Here x is a distance in which fluid can be equilibrium, K_f is fluid modulus, η is viscosity and k is permeability of rock frame. C is a constant term that involves unit conversion among the various parameters as well as allowing rough calibration through our laboratory measurements.

The diffusive flow is dependent on the boundary conditions we impose on the sample. For open boundary conditions, fluid can move in and out of the sample. Under closed conditions, no fluid movement in or out of the sample is permitted. The boudary condition in our case is determined by opening and closing micro-valves in the pore fluid lines.

Measured Low Frequency Data

We have observed this flow effect in the Rim Sandstone with partial saturation. In this case, the rock is measured dry and completely brine saturated (Figure 3). At ultrasonic frequencies, we see the expected effect of brine saturation: a substantial increase in the compressional velocity with brine saturation. When the valves are open, fluid motion in and out of the pore system can occur at low frequencies. This results in a 'drained' case, or a condition where pore pressure will not change with the deformation resulting from the elastic wave. Hence, the bulk modulus will not increase. However, density is increased because of the water saturation. Thus the velocity is lower than for the dry case.

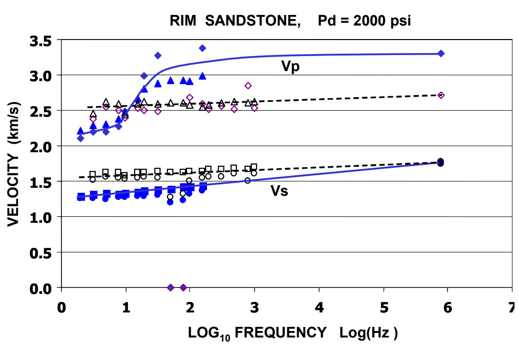

Figure 3. Rim Sandstone, dry and saturated with brine. I n brine saturated case, the microvalves in the pore fluid system are open allowing fluid moving in and out of sample. At low frequency, the sample acts at 'drained' condition. As results, the compressional velocity is lower tha dry case due to density effect.

An injection process can be used to produce a heterogenious fluid distribution. Two cubic centimeters of liquid butane are injected into the brine saturated sample. This results in a hydrocarbon saturation of 20%. As we can see in Figure 4, the effect is small at ultrasonic frequencies, and increases with decreasing frequency. This is what we would expect for fluid motion and pressure equilibration between the two regions. The butane, although liquid, still has a very low modulus. This keeps the pore pressure change small with deformation. At lower frequencies, the brine-saturated zone is more strongly influenced by this pressure equilibration. Applying the flow model (with the adjustable parameters) gives the red line fit to the compressional velocity. Note that the dispersion in shear modulus must also be included in this model calculation.

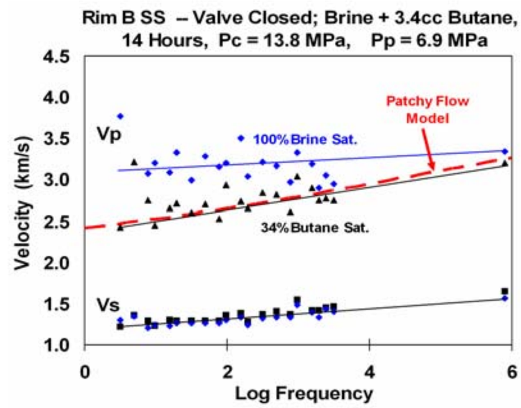

Figure 4. Brine saturated and partially butane saturated Rim sandstone. At lower frequencies, the brine can come into pressure equilibrium with the more compressible butane. The macro flow model fit is shown in red.

Application

Here we are interested in the effects of fluid flow on the moduli and velocities, through the fluid mobility and distance from a gas saturated zone.

As an example of a logging application, we can apply the relaxation relation to the case of a porous and permeable sand. This model consists of a thin gas saturated layer on top of a brine saturated zone.
A uniform shale surrounds the sand. The use of the Cole-Cole relation aids us since both the low frequency and high frequency moduli can be estimated from the log. The 'low frequency' modulus is presumed to be that of the gas sand (3 GPa). The infinite frequency limit will be the modulus of the brine saturated zone as measured as an isolated, homogeneous system (7.5 GPa). These values were chosen to match values observed in a Gulf of Mexico log. The results for bulk modulus, attenuation, and compressional velocity are shown in Figures 5, 6, and 7 respectively.

Under the correct conditions of high fluid mobility and low frequency, we can see that the nature of the gas-water contact can be changed substantially. What appears as a sharp contact at high (logging) frequencies, is smeared into a gradational contact at seismic frequencies.

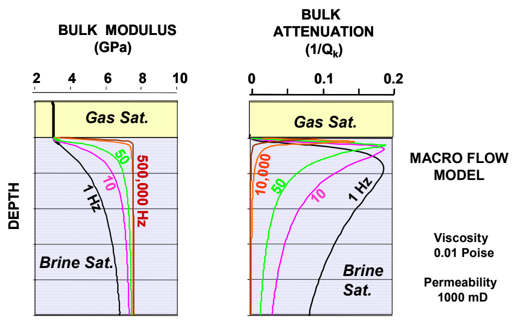

Figure 5. Modeled modulus and attenuation for a gas sand layer on top of a brine saturated zone. At lower frequencies, fluid motion can be significant, blurring the contact and causing high attenuation.

To apply this technique to correct a sonic log of dispersion, we need to know the distance from the gas-liquid contact, porosity, permeability, and frequencies involved. Most of these can be extracted from the logs or derived from the tool characteristics. Permeability is often a difficult value to obtain, but as a first estimate, were could use the relations similar to the form developed by Berg,(1970),

$$k = c_k S_h^2 \phi^m \qquad (2)$$

where S_h is shale content and c_k is a constant.

Conclusions

Pore fluid motion and pressure equilibration can occur over distances similar to the seismic wavelength if fluid mobility is high. The equilibrated rock will have a lower velocity at low frequencies. This fluid motion can also cause higher attenuation. As a result, synthetic seismic traces derived from high frequency sonic tools will be different from the observed low frequency seismic traces.

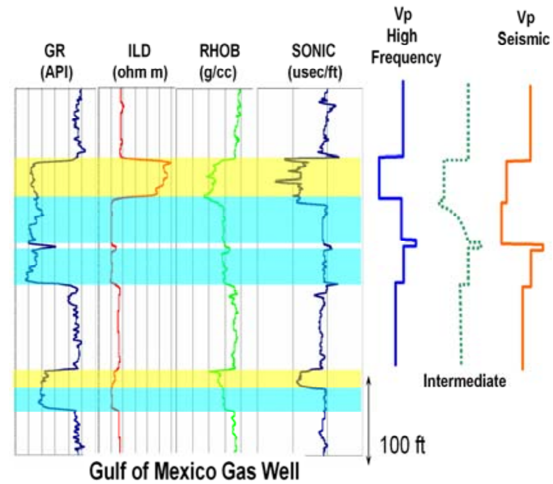

Figure 6. Schematic of flow effects on a logged section. At high (log) frequencies, the contact appears abrupt (blocked blue line). At seismic frequencies, the contact appears gradational (red line).

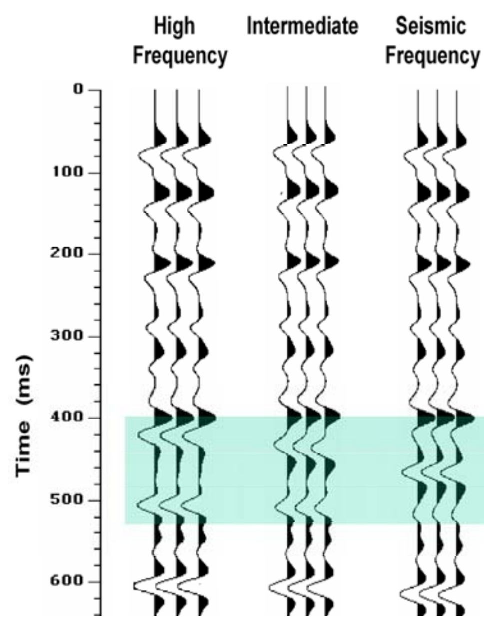

Figure 7. Synthetic traces calculated for the case in Figure 6. The signature at high frequency is substantially different than that at low frequencies.

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Acknowledgments

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