Seismic frequency measurement of velocity and attenuation

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Summary

Velocity dispersion and attenuation in rocks are coupled properties that depend on the pore fluids and fluid flow. Attenuation shows a peak at high partial gas saturation. The amplitude of this peak increases with frequency. With full saturation, velocities rise but dispersion remains approximately constant. A substantial frequency shift occurs with decreasing permeability or fluid mobility. Thus transport properties do have a measurable effect on seismic properties. These effects are dependent on confining pressure, dropping rapidly as pressure increases. For consolidated rocks, these trends are consistent with crack or 'squirt' flow mechanisms. These effects hold strong potential for use as a hydrocarbon indicator attribute or for time lapse (4-D) seismic monitoring.. Estimation of formation permeability may also be possible.

Introduction

Seismic velocity dispersion and attenuation (l/Q) remain underdeveloped and underutilized in geophysics in spite of their strong potential. Both dispersion and Q are strongly dependent on lithology and pore fluid properties, and transport properties and could become powerful interpretation tools. In addition, velocity and l/Q changes due to altered fluid and pressure conditions in a reservoir could dominate the time-lapse (or 4-D) seismic response. However, these effects commonly are not used because of incomplete and contradictory theories, sparse laboratory data, and lack of robust techniques to derive l/Q from log or seismic data. Recently, Klimentos (1995) used the ratio of compressional to shear attenuations as hydrocarbon indicator in well logs. Yamamato et al. (1994) estimated in situ permeabilities based on a modeled response matching measured cross-borehole velocity dispersion. In the future, such applications will be more common in deriving reservoir characteristics.

Dispersion and attenuation are coupled effects in most materials such as rocks (Norwick and Berry, 1972). Theoretically, many models have been proposed for porous media such as those of Biot (1956), O'Connell and Budiansky (1977), Walsh (1994). Divorkin and Nur, (1993), Squirt flow in combined Biot and local (squirt) into a more general theory. Unfortunately, the different mechanisms proposed often give contradictory results.

Wave attenuation and dispersion in vacuum dry rock is relatively negligible. Porous rocks containing fluids show a strong frequency-dependent dispersion and l/Q (Spencer, 1981). Variations in fluid properties such as modulus, viscosity, and polarity have a strong influence (Clark, 1980; Winkler et al., 1982; Murphy, 1983; Tittmann et al., 1984; Jones, 1986; and Tutuncu et al., 1995). These results indicate that the dominant mechanism is the interaction and motion of fluid in the rock frame rather than intrinsic losses either in the frame or fluids themselves. Squirt flow is believed to be the primary loss mechanism in consolidated rocks although the inertial Biot mechanism may be important in highly permeable rocks (Vo-Thanh, 1990; Yamamato et al., 1994).

In this paper, we present data collected over a broad low frequency band. Our measurements focus on partial fluid saturation and fluid mobility related to permeability. Ultimately, this type of data will resolve the mechanisms involved and help develop attenuation into a useful geophysical tool.

Measurements

For our low frequency measurements, we use a forced deformation, or stress-strain technique (Figure 1) described by Smith et al. (1988) and similar to that employed by Spencer (198 1) and Paffenholz and Burkhardt (1989). Samples are mounted in parallel with an aluminum- standard. A sinusoidal force is applied and rock modulus is determined by the ratio of the sample to standard strains. Determination of axial strain provides Young's modulus, horizontal strain yields Poisson's ratio. For an isotropic medium, these two values permit calculation of all other elastic properties. We calculate velocities from moduli using the known sample density Attenuation is derived from the phase shift between driving force and sample strain.

Measurements for our investigation primarily were made in the frequency range from 5 to 2500 Hertz. This encompasses the seismic range and extends into range of recently developed low frequency logging tools. Values become strongly amplitude dependent at higher strain levels, so measurements must also be restricted to levels similar to those in seismic and sonic data. Additional data was collected at megahertz frequencies using standard ultrasonic techniques.

Attenuation and velocity dispersion at seismic frequencies

The samples assembly (Figure 1) is mounted in the deformation frame contained in a pressure vessel . Temperatures, confining and pore pressures can be controlled independently. Gas is used as a confining medium and pore fluids can be circulated during the experiment. The sides of the sample are sealed with a thin epoxy coating to minimize boundary flow effects.

Figure 2 shows the effect of both frequency and saturation on l/Q in Berea Sandstone. Under vacuum dry conditions, little attenuation is observed, confirming the necessity for pore fluids to produce measurable attenuation. As brine saturation increases, a l/Q plateau is reached. At high brine saturation (about 90%), attenuation peaks, but then drops again at 100% saturated. There is a strong frequency dependence on l/Q. Both the level and peak values drop with increasing frequency. Thus attenuation effects seen in ultrasonic or logging data may not occur in the seismic range.

A Cole-Cole type of model model for compressional velocity dispersion linked to attenuation is shown in Figure 3. The maximum change in velocity corresponds nearly to the attenuation peak as we go from unrelaxed conditions at high frequency to relaxed at low. Here, the controlling factor would be fluid mobility or permeability. Under the most mobile and compliant conditions of partial saturation, velocities would be lower and dispersion obvious in the seismic range. For complete brine saturation, the overall modulus or velocity increases, but dispersion stays in the same frequency range. If we could now lower permeability by several orders of magnitude, our dispersion curve would shift to lower frequencies as the pore fluid is now less mobile and the rock takes longer to relax.

This permeability/mobility experiment was performed on a sandstone and the results are shown in Figure 4. Initially, at partial brine saturation, pore fluids move easily and the dispersion is easily visable (dashed lines). Full brine saturation increases the velocity, but leaves the dispersion in about the same frequency band (light lines). However, when the rock was flooded with distilled water, clays in the pore spaces swelled and decreased permeability by two orders of magnitude. The result is that the dispersion is shifted to lower frequencies since fluid motion is slower and relaxation times longer. This behavior is consistent with squirt-type flow.

Conclusions

Measurements show clearly that seismic wave attenuation is substantial for partially saturated rocks. Changing fluid mobility, as indicated by changing permeability, alter the dispersion and frequency response. Dispersion shifts to lower frequencies with decreased fluid mobility. These data are in agreement with local or squirt flow mechanisms within the rock. These results indicate that l/Q and dispersion might be used to derive both fluid and transport properties of rocks.

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Attenuation and velocity dispersion at seismic frequencies

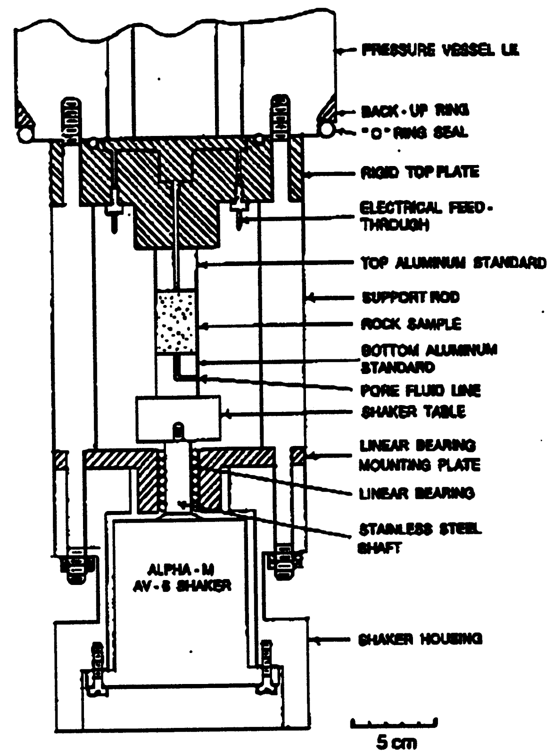

Figure 1, Low frequency measurement device schematic

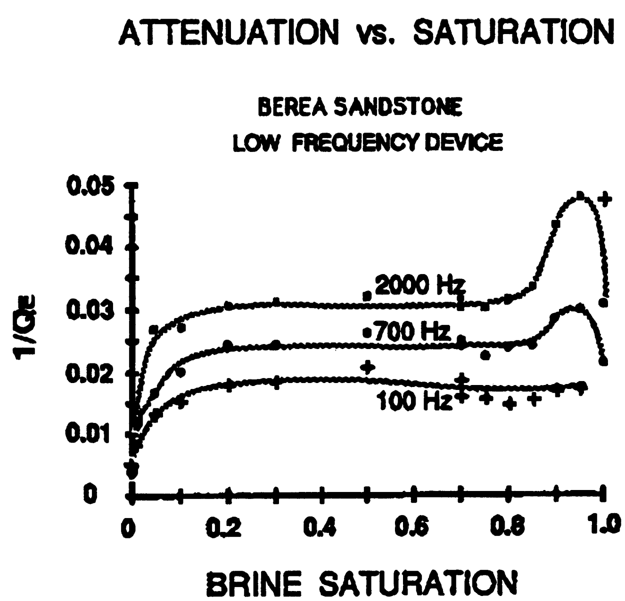

Figure 2. Attenuation in sandstone as functions of brine saturation and frequency

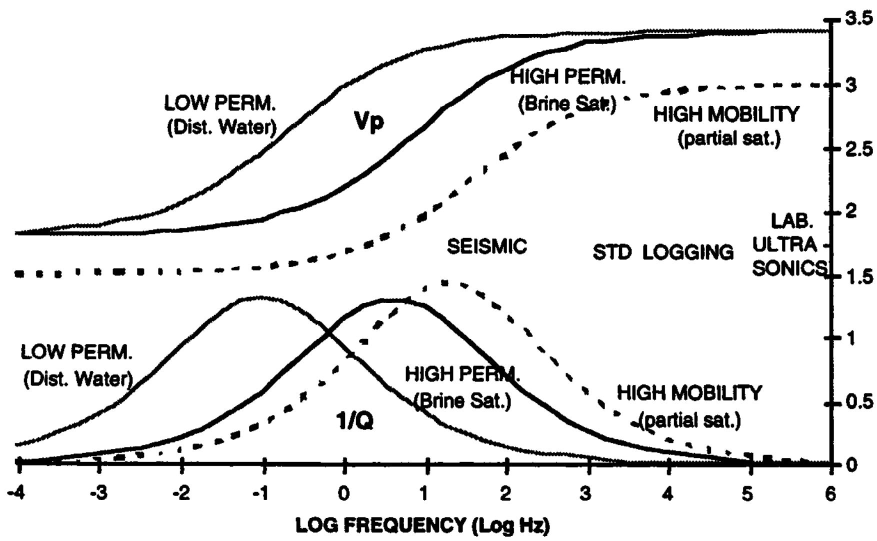

Figure 3, Cole-Cole velocity (top) and attenuation (bottom) relationships. These generalized trends are predicted using the ‘squirt’ flow concept. High mobility fluids under partial gas saturated conditions show the highest frequency range, intermediate mobility (brine), and low mobility (distilled water) have lower frequency ranges.

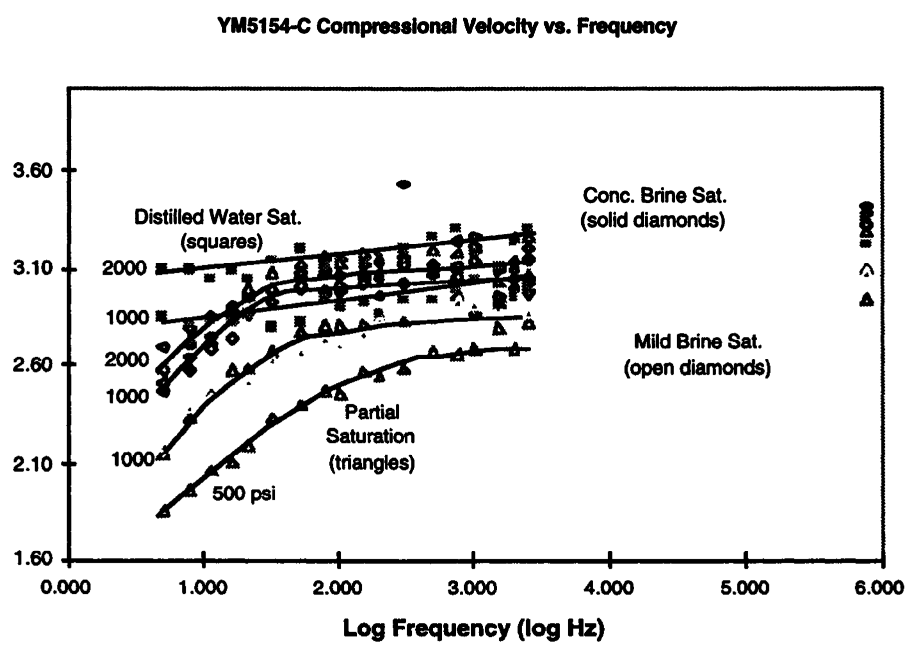

Figure 4. Measured Compressional velocities on a water-sensitive sample. Partial saturated (dashed line) and brine saturated (thin line) show a strong frequency dependence. Distilled water (heavy line) have dispersions shifted to lower frequencies.