Seismic Attenuation as a DHI Tool: Laboratory Measurements to Understand the Effect of Fluids and Pressure on Elastic Wave Attenuation

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Summary

Seismic attenuation is a fundamental property of rocks and is defined as the inverse of quality factor (1/Q, where Q is the quality factor). Due to lack of reliable data, attenuation is very poorly understood. Most of the published attenuation measurements are done in megahertz frequency range and thus are not applicable to low frequency seismic waves. To address this issue, a low frequency, low-amplitude apparatus was built to measure seismic velocities and attenuation.

The apparatus was calibrated using a standard material with known velocities and attenuation. A series of experiments were then carried out to understand the effect of pressure, fluid saturation and mobility on frequency dependant velocity and attenuation. Ultrasonic velocity measurements were also carried out to measure velocity dispersion. Different modes of attenuation are related to each other and the inequality relationship changes with the saturation state. Boundary conditions can also change the attenuation and velocity values for a fully saturated rock: open boundary causes a drop in velocity and an increase in attenuation. This effect is only observed at low-frequencies and depends on the fluid mobility. These measurements confirm that velocity and attenuation are dependant on viscosity and permeability and the relaxation frequency shifts towards low or high frequency by increasing or decreasing the fluid mobility respectively. Partial gas saturation produces maximum attenuation and could be a potential tool for fizz-gas detection.

Introduction

Seismic waves, as they propagate through a material loose a fraction of their energy (amplitude) in the form of heat and this loss is in addition to the losses incurred due to transmission, scattering, diffraction and spherical divergence. The conversion of seismic energy into heat is called intrinsic attenuation and is measured in terms of Quality factor (Q), where 1/Q is the energy lost per cycle of oscillation. Laboratory measurements of attenuation and velocity on rock samples under varying conditions of pressure, saturation, temperature, strain and frequency have been reported in literature. Most of these measurements are done in frequency-amplitude space outside the seismic range. In order to understand the effect of fluids and pressure on seismic waves and to extract useful information from seismic attenuation, it becomes essential to measure these seismic attributes under the seismic frequency-amplitude space.

A schematic diagram of the apparatus used for the low-frequency, low-amplitude seismic attenuation and velocity measurement, is shown in Figure-1.

The shaker at the bottom produces vertical oscillation at known frequencies. A cylindrical rock sample is placed between the shaker and the vessel lid. Vertical and horizontal deformation is produced in the rock sample due to the oscillations generated from the shaker. These deformations are picked by strain gages, which are placed on the surface of the rock sample. Fluid is injected into the sample with the help of pore fluid lines connecting the top and bottom of the sample. The sample is jacketed and the pore pressure can be controlled independently. The pore fluid lines can be opened or closed to simulate open and closed boundary conditions respectively. The entire assembly is then

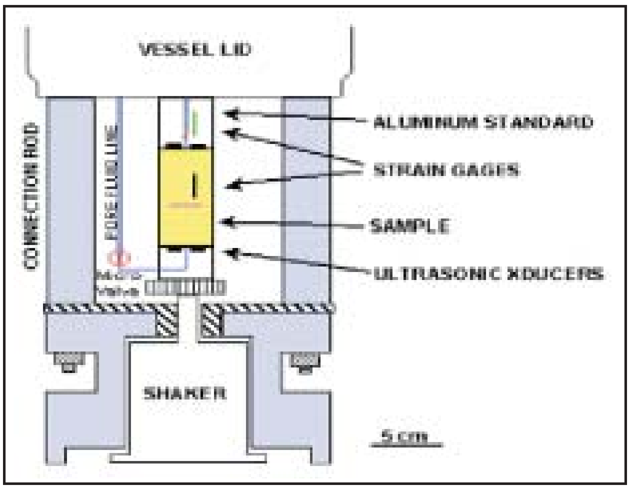


Fig. 1: Schematic diagram of the low-frequency apparatus.

kept inside a pressure chamber to apply confining pressure.

Theory

The observed seismic waves do not travel with a simple elastic propagation. Amplitudes are lost both in time and distance. The loss is due to spherical divergence, scattering, diffraction and transmission. When the material is not purely elastic there is a loss in excess to the above mechanisms. This phenomenon is called intrinsic attenuation and is characteristic of linear viscoelastic materials. For viscoelastic materials the strain lags the applied stress and the modulus that relates the applied stress to observed strain is a complex quantity. This complex modulus causes a phase shift between stress and strain.

The most common measure of attenuation is Q or the quality factor and its inverse $Q^{-1.}$ O'Connell and Budiansky [1977] have discussed various definitions of Quality factor. Quality factor is related to the phase lag between applied stress and observed strain as $\frac{1}{Q} = \frac{M_I}{M_R} = \tan\theta$, where M_I is the imaginary component of the complex modulus and M_R is the real component and θ is the phase angle in radians. Different modes of deformation produce different modes of attenuation. For a purely extensional mode stress-strain phase lag will give Q_E, which is the Young's modulus loss parameter. The other stress state attenuation parameters (Q_P, Q_S, Q_K) are related to each other through these four equations [Winkler and Nur, 1979]:

$$\frac{1}{Q_S} \cong \frac{(1+\nu)\frac{1}{Q_E} - \nu \tan\theta_\nu}{1+\nu}$$

$$\frac{(1-\nu)(1-2\nu)}{Q_P} = \frac{1+\nu}{Q_E} - \frac{2\nu(2-\nu)}{Q_S}$$

$$\frac{3}{Q_E} = \frac{1-2\nu}{Q_K} + \frac{2(1+\nu)}{Q_S}$$

$$\frac{1+\nu}{Q_K} = \frac{3(1-\nu)}{Q_P} - \frac{2(1-2\nu)}{Q_S}$$

, where Qp, Qs, Qk are the P-wave, S-wave and the bulk attenuation quality factors respectively and θ_ν is the Poisson's ratio phase lag and ν is the Poisson's ratio.

Results

Effect of differential pressure

Differential pressure is defined as the difference between confining or overburden pressure and the pore or hydrostatic pressure. With and increase in differential pressure the cracks and the compliant pore spaces close. The rock becomes stiffer and the bulk and the shear moduli increase. Figure-2 shows the increase in Vp and Vs with increasing differential pressure for a dry rock.

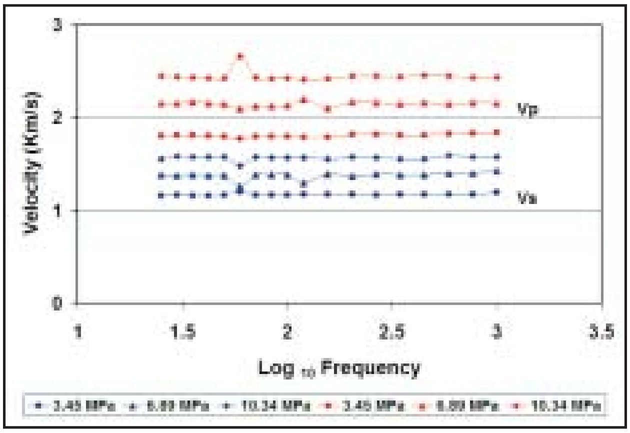


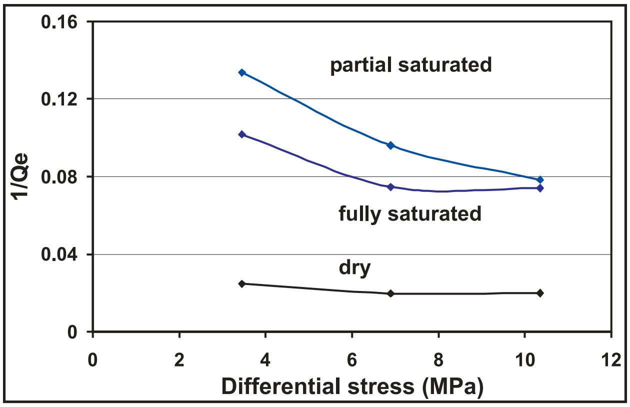
Fig. 2: Rim sandstone, compressional and shear velocity as a function of frequency and varying confining pressure. Porosity=0.19 and permeability=300 md.

A sphere rock model is a well known model used to describe the skeleton of a rock. This model consists of rounded grains with varying degree of cementation. When a wave propagates through such a medium, grains slide along the contact boundary. This is source of frictional attenuation in rocks. With an increase in the stiffness of the rock, the inter-granular friction reduces resulting in a drop in frictional attenuation. Fluid flow between pore spaces is another mechanism of attenuation. With an increase in differential pressure and closing of compliant pore spaces the fluid flow inside the rock matrix is reduced. Thus, increased differential pressure causes a sharp drop in attenuation. Figure-3 shows the effect of increasing differential pressure on $1/Q_E$ for a clastic rock. This suggests that with increase in depth of burial attenuation drops.

A similar measurement on a carbonate sample showed no appreciable change in either velocity or attenuation.

Effect of Saturation

Attenuation for fully or partially saturated rocks is



Fig,3: Rim sandstone, extensional (Young's) 1/Q in dry, partially saturated and fully saturated rock with varying differential pressure (measurement frequency 1KHz). Porosity=0.19 and permeability=300 md .

higher than for dry rocks and depends upon the degree of saturation, fluid type and frequency in complicated ways [Tittmann et al., 1981; Clark et al., 1980]. There are several theories that explain the attenuation mechanism at partial saturation. Mavko and Nur [1979] use the *Squirt flow* model where liquid droplets move in response to compression in cracks as waves pass through rock. White [1975] used *gas pocket* model where the gas zones act as regions of low compressibility. Increase in fluid saturation would cause more fluid to flow through pore spaces and would cause an increase in attenuation.

Depending on the state of saturation the different modes of attenuation follow any one of the three inequalities that constraint them. Winkler K. And Nur A. [1979] derived these inequalities based on the mathematical relation between various modes of attenuation.

$$Q_S > Q_E > Q_P > Q_K \quad (1)$$
$$Q_S = Q_E = Q_P = Q_K \quad (2)$$
$$Q_S < Q_E < Q_P < Q_K \quad (3)$$

For partial saturation the modes follow the first relation wherein the compressional attenuation (1/Qp) is higher than Shear attenuation (1/Qs). At full saturation the bulk and compressional attenuation values drops because there are no compliant pore spaces to move the fluid around. For full saturation the third inequality holds true.

The boundary condition of the pore fluid system plays an important role. By opening and closing the micro valve we can simulate open and close boundary conditions respectively. Figure-4 shows the relation between different modes of attenuation for saturated open boundary measurement done on Rim sandstone sample. With open valves, the low frequencies (<100 Hz) behave as if the rock is partially saturated even when the rock is fully filled with brine (different modes follow the first inequality). The specific range of low-frequency depends on the rock and the fluid properties. The reason for this behaviour is that at low-frequencies the open boundary allows fluid to move in and out of the sample and equilibrate with the surrounding pressure. At high frequencies there is not enough time for fluid to equilibrate with the external pore fluid. Thus at high frequencies the different modes follow the third inequality and behave as if the rock is fully saturated.

Open and closed boundaryeffect the compressional velocities also. Figure-5 compares the open and closed boundary velocities for Foxhill's sandstone sample. For low-frequency the open boundary compressional velocity is less than the closed boundary because at such frequencies the fluid pressure equilibrate simulating a drained condition. It was interesting to observe that the open boundary velocity was even less than the dry rock velocity because of the density effect. There is no effect of boundary conditions on shear velocity.

The compressional velocities at different saturations are often estimated using effective fluid model [Domenico, 1977; Mochizuki, 1982]. The velocities measured at low frequencies are not consistent with ultrasonic measurements done in the laboratories. If laboratory measurements done at ultrasonic frequencies are used to predict the seismic response at partial saturation then there will be errors.

Figure-6 shows the ultrasonic and low-frequency compressional velocities as a function of saturation. There is a considerable difference specially at partial saturations and this difference can be explained using White's *gas pocket* model and the *squirt flow* (Mavko and Jizba, 1991).

In the *gas pocket* model separate gas and fluid phase is present in a regular cubic lattice geometry. In the *squirt/local flow* model there is localized movement of fluid from region of high-pressure to low-pressure.

At-low frequencies the liquid has enough time to equilibrate with the gas phase and thus the compressional velocity drops. At ultrasonic frequencies, there is no equilibration due to lack of time, which results in stiffening of the rock-fluid matrix due to unrelaxed fluid pressure. At full saturation, the low frequency and ultrasonic velocities

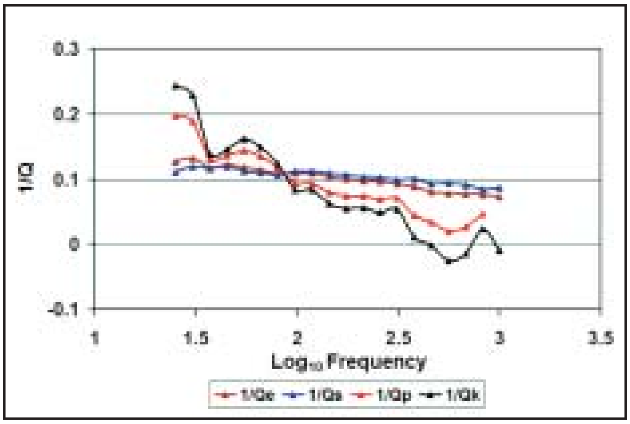


Fig.4: Rim sandstone, variation of extensional, shear, compressional and bulk 1/Q values with frequency at 100% saturation (open boundary). Note the reversal of order as we move from low to high frequency. Differential pressure=6.89 MPa.

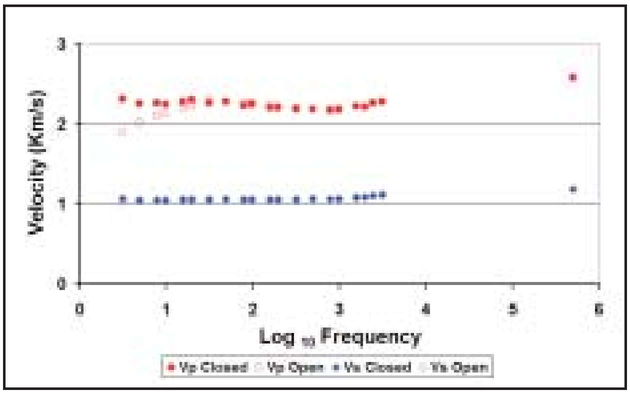


Fig.5 : Foxhill's sandstone, velocity vs frequency for open and closed boundary case. The sample is 100% saturated and the confining pressure is 17.3 MPa and the pore pressure is 6.9 MPa. Note the frequency at which both open and closed P-wave velocities become equal. Porosity=27% and permeability=100md.

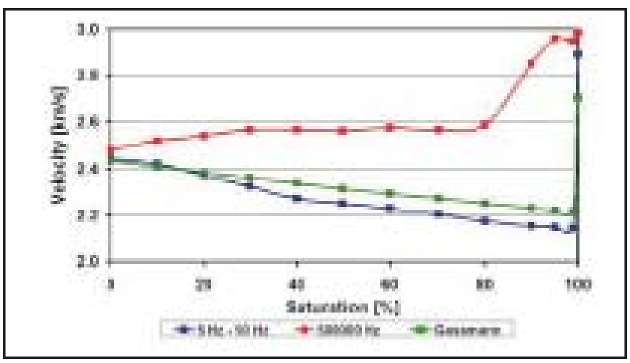


Fig.6: Rim sandstone, variation of extensional, shear, compressional and bulk 1/Q values with frequency at 100% saturation (open boundary). Note the reversal of order as we move from low to high frequency. Differential pressure=6.89 MPa

similar because there is no low-pressure region for equilibration. The change in attenuation with increasing brine saturation is shown in Figure-7. With a slight amount of brine added both the compressional and shear attenuation

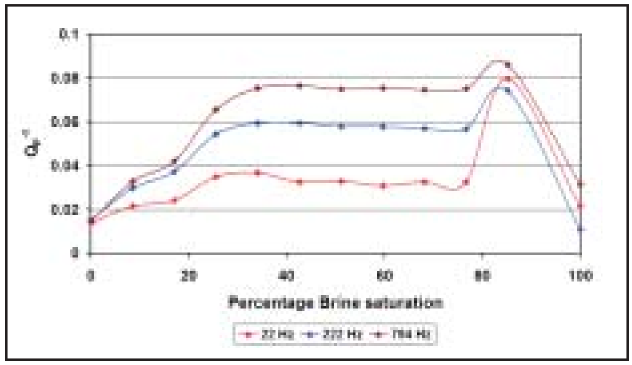


Fig. 7: ITF-51, Compressional attenuation with changing brine saturation. Differential pressure=6.89 MPa.

increases. As brine is injected few monolayers wets the grain contacts and softens the rock causing an increase in attenuation [Clark et al., 1980]. At residual gas saturation (~95% brine saturation), 1/Qp shows a jump in attenuation and is very significant. Compressional attenuation is due to bulk flow and at near full saturation it requires zones of high compressibility for the liquid to move and equilibrate. At residual gas saturation the amount of liquid is maximum and also there is small amount of gas present promoting liquid flow resulting in very high values of compressional attenuation. At full saturation the values drop and become almost equal to the dry attenuation values. In the case of a producing reservoir the gas water transition zone should produce maximum attenuation because of the reasons mentioned above and thus attenuation can be used as a tool to monitor the transition zone. Abnormally high attenuation values can also be used to delineate low-gas saturation reservoir.

Effect of mobility

Permeability of rocks and fluid viscosity are two important factors that describe fluid mobility inside a rock. Increase in viscosity (η) decreases the mobility and increase in permeability (κ) increases the mobility of the fluid. Viscosity of fluids can be changed with a change in temperature as in the case of Enhanced Oil Recovery processes (EOR). Nur and Simmons [1996a] have shown that the viscosity effect on attenuation is frequency dependant and is related to some relaxation type mechanism. The peak attenuation frequency (ω_c) is dependant on the fluid mobility ($\omega_c \propto \frac{\kappa}{\eta}$). According to the *squirt theory* the peak should move towards lower frequency as the mobility is decreased. This is because the fluid will require more time to come to relaxed state corresponding to a lower frequency of the propagating wave. Attenuation on Uvalde carbonate sample (heavy oil in pore spaces) was measured for three different temperatures. The result is shown in Figure-8 and shows that with increase in temperature the attenuation increases and lower frequencies have higher attenuation compared to higher frequencies. Thus the peak shifts towards lower frequency as the temperature is lowered.

Permeability is another factor that influences fluid mobility. An increase in permeability would cause an increase in mobility. Four samples with similar porosity but different permeability were measured. Figure-9 shows the result of these measurements. It is clear that the low permeability rocks experience higher attenuation compared to high permeability rocks. If we were to measure the entire spectrum then we would find that with increase in permeability the peak attenuation frequency increases.

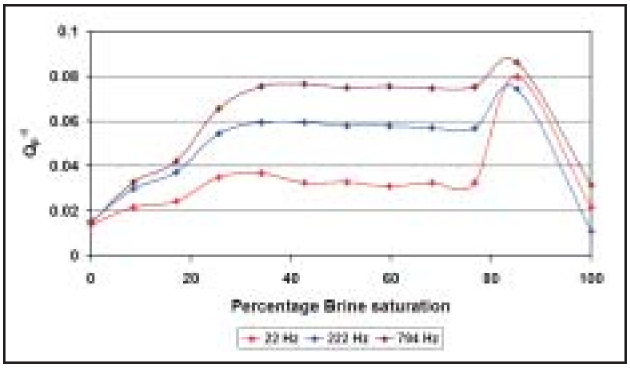


Fig. 8 : Uvalde carbonate, shift in attenuation peak with change in viscosity. The viscosity change is due to change in temperature of the heavy oil. Confining pressure=10.34 MPa. Permeability=550 md.

Conclusions

Wave propagation in an anelastic material causes loss in energy which is called intrinsic attenuation. Attenuation is related to velocity dispersion and both in turn are strongly dependant on fluid type, saturation, mobility and distribution. Thus, attenuation measurements are useful in estimating the fluid properties like viscosity, degree of saturation, zones of high permeability. Attennuation is also dependant on differential pressure which increases with depth of burial.

Attenuation and dispersion in dry rocks is negligible. With increase in differential pressure attenuation decreases due to closing of compliant pore spaces and velocities increase for the same reason. The rate of increase in velocity or the rate of decrease in attenuation is high for low differential pressures reduce with increase in differential pressure. At partial saturation attenuation increases and is twice as much as shear attenuation. At full saturation compressional attenuation drops considerably and is one third of shear attenuation. Open and close boundary conditions make a significant difference in compressional velocity and attenuation for fully saturated rock. Open boundary allows macroscopic flow between regions of low compressibility to high compressibility. Only low-frequencies can detect open boundary conditions and are thus applicable to seismic wave propagation. A change in mobility of the fluid inside the rock shifts the peak attenuation frequency or the relaxation peak. These kinds of measurements are very useful in thermal enhanced recovery processes, where the change in viscosity can be detected through attenuation measurements [Ken Headlin, 2001]. These attenuation measurements are also useful in identifying zones of high and low permeability.

At partial saturation there is significant velocity dispersion as low frequency compressional velocity decreases and ultrasonic velocity increases with increase in liquid saturation. At very low gas saturations attenuation is maximum. This result is significant because at gas-oil or gas-water contact in homogeneous reservoir rocks, there is a transition zone where gas saturation varies through a wide range. This transition zone will be the zone of maximum attenuation. Alos, during production as the pressure drops, the gas may come out of solution creating distributed pockets of free gas and cause very high attenuation. Attenuation measurements could be used to monitor the transition zone. and elastic logs for both the water and gas-charged scenarios. For QC purposes the same attributes were computed for an additional six wells in the South and South West Tapti seismic volume. Where shear data were not recorded, the Modified Gassmann equation was used to generate Vs logs. The results were cross-plotted to determine which attributes gave maximum separation of gas sands compared to water-wet sands and shales, (Fig. 2).

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