

Seismic Attenuation: Observations and Mechanisms

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Summary

Seismic attenuation and dispersion can be caused by numerous distinct mechanisms. Observed or proposed mechanisms include mineral surface-fluid interaction, microscopic squirt between pores, macroscopic fluid motion between heterogeneous regions, and bulk loss within the fluid phase itself. The lack of an understanding of these various processes renders interpretation of attenuation-related attributes problematic at best. Direct measurement of seismic attenuation ($1/Q$) and velocity dispersion in the laboratory help discriminate among these mechanisms and ascertain which dominate for particular lithologies or saturation conditions. Fluid motion is a primary mechanism in porous, permeable clastics. In shales, however, bulk fluid motion is inhibited and clay particle interaction with bound water may dominate. Heavy, viscous fluids themselves show bulk losses independent of a rock matrix. All these loss mechanisms are frequency dependent, so observations of $1/Q$ made at seismic frequencies usually will not agree with sonic log measurements, which, in turn, will not agree with ultrasonic data.

Introduction

Seismic attenuation measurements have long been proposed as a method to identify fluids or zones of high permeability in situ. Field data is now improving to the point where qualitative estimates of $1/Q$ are possible, based largely on frequency content. However, interpretation is still hampered by a lack of understanding of the primary mechanisms involved in intrinsic $1/Q$. Direct observation of loss and dispersion within the seismic frequency band in the laboratory point toward several independent, competing mechanisms.

Completely dry rocks have almost no attenuation (Tittmann, et al., 1980). Even small amounts of volatiles are enough to cause appreciable loss (Clark, et al., 1981; Vo-Thant, 1995). Losses due to fluid motion between pores will then be added to the overall $1/Q$ (Murphy, 1982). A different mechanism is macroscopic fluid flow between areas of heterogeneous saturation or rock compliance (White, 1975; Gist, 1994). In contrast, shales can show substantial $1/Q$ even though macroscopic flow is prevented. Such shale losses are likely related to grain-bound fluid interaction or perhaps motion of fine fluid menisci (Brunner and Sptezler, 2001). However, Ursin and Toverud (2002) have pointed out that the various

mechanisms are difficult to differentiate over the narrow seismic band.

Attenuation is a fundamental intrinsic property of rocks causing energy loss and is related to velocity dispersion. 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 1.

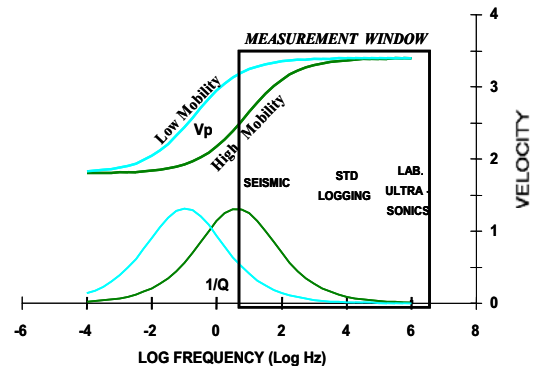


Figure 1. Cole-Cole relation couples velocity and attenuation as functions of frequency. The frequency range of our laboratory measurements is indicated. Also shown is the effect of high fluid mobility and low fluid mobility.

Measurement Techniques

Several techniques are available to measure $1/Q$. The most common laboratory method is the spectral ratio technique which compares the frequency content of ultrasonic waves passing through a standard to those through a rock sample (Toksoz et al., 1977).

To reach the seismic frequency band, use a forced-deformation apparatus similar to that used by Spencer (1981). As important, strain amplitudes must also match those characteristic of seismic waves, otherwise different deformation mechanisms come into play. Samples are typically cylinders 5 cm in length and 3.8 cm in diameter. Frequencies range from about 0.3 Hz to 2,000 Hz. Strain amplitudes are kept below 10^{-7} . Small 'Micro-valves' control fluid movement in and out of the sample.

For low frequencies, a low amplitude sinusoidal stress is applied axially to the assembly consisting of the sample

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and aluminum standards. Relative strain amplitudes of the aluminum versus sample yield the moduli of the rock. Phase angles between the standard and rock permit attenuation to be calculated.

Pore Fluid Motion

We have seen in several of our low frequency experiments, how fluid flow and fluid type can influence the seismic attenuations and velocities. 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, 's squirt' flow mechanisms can operate over a small distance, and adjacent pores can reach equilibrium (O'Connell and Budianski, 1977; Mavko and Nur, 1975). With high mobility, a more global or 'Macro' flow can occur on a scale approaching to the seismic wavelength (White, 1975, Pride et al, 2003).

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.

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

$$\tau = C \frac{x^2 \eta}{K_f k} \tag{1}$$

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.

We have observed that an increase in permeability shifts the relaxation peak to higher frequency. Residual gas saturation produces high attenuation values. Attenuation values drop and velocities increase as we increase the differential pressure. These properties can be used in monitoring production effects using time lapse surveys.

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. Boundary conditions in our case are determined by opening and closing micro-valves in the pore fluid lines.

Different modes of attenuation (bulk $1/Q_K$, compressional $1/Q_p$, Young's $1/Q_E$, and shear $1/Q_s$) are related to each through inequalities, which change with saturation state. At partial saturation, $1/Q_K$ is largest and $1/Q_s$ smallest. At full saturation, this relation is reversed. Also at full saturation opening the sample boundary can significantly change the velocity and dispersion values.

The different modes of attenuation follow one of the three inequalities which change with the saturation state (Winkler and Nur 1979):

- 1) $\frac{1}{Q_s} < \frac{1}{Q_E} < \frac{1}{Q_p} < \frac{1}{Q_K}$ (low V_p/V_s)
- 2) $\frac{1}{Q_s} = \frac{1}{Q_E} = \frac{1}{Q_p} = \frac{1}{Q_K}$, (2)
- 3) $\frac{1}{Q_s} > \frac{1}{Q_E} > \frac{1}{Q_p} > \frac{1}{Q_K}$ (high V_p/V_s)

where S,E,P and K stand for shear, Young's, compressional and bulk modes. Figure 2 shows the relation between different modes of attenuation at open boundary conditions. For open valve low-frequencies behave as if the rock is partially saturated (mode 1 above). This is due to the fluid movement across the boundary. At high frequencies (> 100 Hz), there is insufficient time for fluid to flow and to reach pore pressure equilibrium with the external system. The rock behaves fully saturated, and shear losses are highest (mode 3 above).

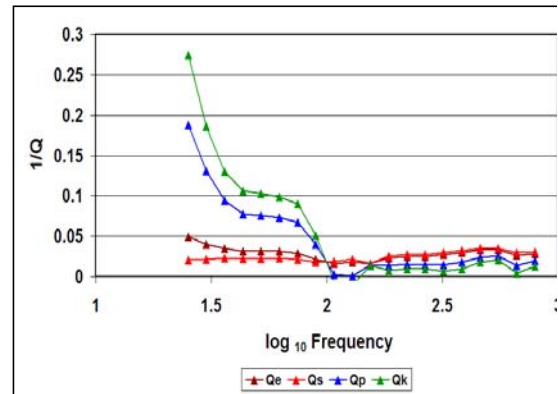


Figure 2: 100% brine saturation. Open valve allows to simulate open boundary condition. Saturated $1/Q_p$ is very small and is nearly equal to dry $1/Q_p$. At low frequencies, fluid can flow in and out of the sample, and $1/Q_p$ and $1/Q_k$ dominate.

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Attenuation Anisotropy

Rock fabric, deformation and fluid flow can be strongly anisotropic. As these factors control attenuation, we expect losses can be greatly different for different directions of propagation. One straight forward way to test this is by comparing ultrasonic quality factor (Q) measured on the same sample but with different orientations. Figure 3 shows the ultrasonic compressional quality factor (Qp) for both vertical and horizontal wave propagation through a chalk sample. We see higher losses (lower Q) for the vertical direction. Since the vertical direction is more compliant, more fluid motion may result from wave propagation in this direction. Note that where as velocities usually have anisotropies of a few percent, attenuations can vary by factors of two or three in different directions.

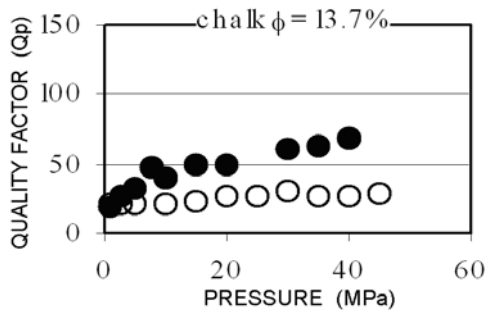


Figure 3. Quality factor (Qp) anisotropy in a chalk sample measured ultrasonically. Horizontal Qp (solid dots) is higher than the quality factor measured vertically (open circles).

Shale Attenuation

Attenuation is also apparent in shale samples. In the case of shales, the material is inherently anisotropic, and measurements must be made in several directions on samples of at least two orientations. Directions x_1 and x_2 are parallel to bedding and x_3 is orthogonal to bedding. Example results can be seen in Figure 4, where the quality factor in the x_3 direction (Q_{33}) is plotted as a function of frequency. Quality factor here is defined as the ratio of the real modulus component to the imaginary component (i.e. $Q_{33} = \text{Re } C_{33} / \text{Im } C_{33}$). As can be seen in Figure 4, Q_{33} is strongly frequency dependent. Thus, attenuation measured in the seismic band will not equal that measured with sonic logs or ultrasonically. This observed attenuation suggests a separate relaxation mechanism. Because of the low permeability and fluid mobility, bulk fluid motion is inhibited. More likely, interactions among the clay

particles and between the clays and bound water are responsible. Data on shales are sparse, and much more work is required to fully define their behavior. Note that since shales and similar rocks form the bulk of the back ground lithologies, normal seismic “Q” compensation should be compared to shale values, not sand values.

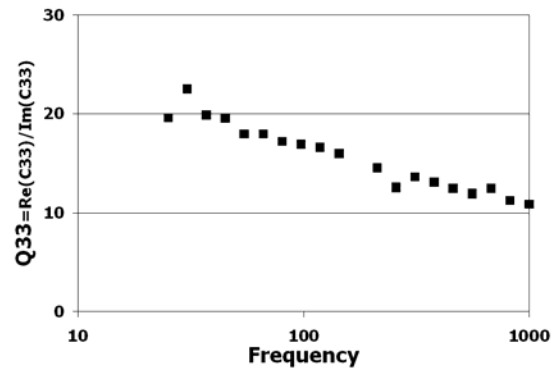


Figure 4: Frequency dependence of quality factor Q for a shale sample with 28% porosity. Q decreases (attenuation increases) with increasing frequency.

Liquid Phase Attenuation

Some liquids will themselves have high 1/Q and dispersion. This is particularly true for very heavy oils which are in a transitional between liquid-like and solid-like behavior. An example is shown in Figure 5. This oil has an equivalent API gravity of -5. It is sufficiently stiff that it can be mounted and the elastic properties measured as if it were a true solid. The attenuation is large and peaks around 50 Hz. This type of behavior is similar to polymers and glasses. One intriguing development can be seen by comparing the 1/Q measured in the fluid with that measured in the rock containing this oil. Simply multiplying the fluid losses by the rock porosity give a reasonable match to the rock values. In addition, the frequency dependence of the saturated rock is similar to the oil. This kind of seismic attenuation due to intrinsic losses in the fluid itself has largely been overlooked. This mechanism may prove a dominant process for the monitoring of heavy oil sands.

Conclusions

Several distinct mechanisms are suggested for the attenuation and dispersion observed in rocks. Behaviors can be quite variable depending on conditions, fluid types, saturations, lithologies etc.

- Volatile-mineral interaction .

Small amounts of volatiles produce initial 1/Q at

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low saturations

- Bulk fluid motion dominates for permeable clastics. $1/Q_p > 1/Q_s$ for patchy saturations and where fluid motion is possible. $1/Q_s > 1/Q_p$ for complete brine saturation with bulk fluid motion prevented.
- Shale losses and dispersions are probably controlled by clay particle interactions with each other and the contained bound water.
- Viscous fluids can have their own internal bulk viscous and shear losses which then contribute to the overall rock attenuations.

The specifics of these mechanisms will be further refined as additional experimental data are collected. Other mechanisms may be possible, and could become dominant under different conditions. These numerous loss types and controlling parameters must be taken into account when any attempt is made to interpret attenuation-related attributes extracted from seismic data.

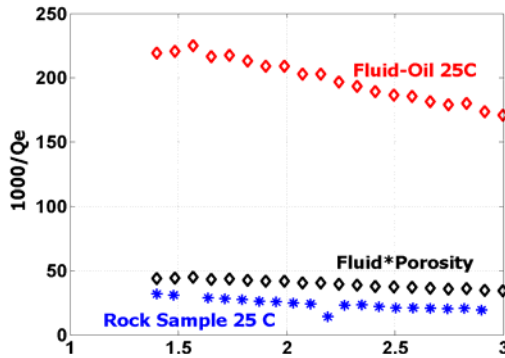


Figure 5: Measured $1/Q$ in both a very heavy oil (red) and a carbonate containing this oil (blue). Simply multiplying the fluid $1/Q$ by porosity brings the magnitude of loss in the fluid phase similar to that in the saturated rock (black). Note the similarity in frequency dependence.

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