Moduli dispersion and attenuation in limestones in the laboratory

L. Adam and M. Batzle, Center for Rock Abuse, Colorado School of Mines*

SUMMARY

There is growing interest in using seismic attenuation for reservoir characterization. We measure limestone samples in the laboratory to analyze attenuation and elastic moduli as a function of frequency from 3 Hz to ultrasonic. We observe that there is a positive correlation between bulk modulus dispersion and permeability. We also measure different modes of attenuation and find that the attenuation in our fully-saturated samples is mostly due to bulk compressibility losses. We observe that attenuation significantly increases when brine replaces a light hydrocarbon.

INTRODUCTION

The analysis of acoustic elastic wave properties such as velocity and amplitude is common practice in reservoir rock physics. With knowledge of these properties, enhanced oil recovery in reservoirs can be monitored through observed changes in velocity and amplitude (attenuation) of seismic waves.

The frequency dependence of moduli in a material or rock is closely related to the attenuation of waves. In the extreme case of no modulus dispersion, there is no attenuation. In this research we explore the velocity and modulus dispersion as well as attenuation for three limestone samples for time-lapse seismic applications. We measure these samples in the laboratory over a range of frequencies to study variations in the intrinsic attenuation as a function of fluid content, and rock permeability at reservoir pressures. In the laboratory we are able to measure rock properties such as the bulk and shear modulus, at seismic and ultrasonic frequencies. At seismic frequencies, we apply a sinusoidal stress and compare the strain on the rock sample to a reference. The moduli are then estimated from the amplitude of the strain signatures, while attenuation (the inverse of the quality factor Q) is estimated from the phase lags of the different strains (Batzle et al., 2006). At ultrasonic frequencies we measure the time of flight of a wave transmitted through the rock core.

We investigate the relation of permeability to attenuation, as well as changes in attenuation for different fluids injected in the pores. This latter analysis has potential application for enhanced oil recovery monitoring: a change in Q might contain valuable information about a change from oil to brine saturation, and could be used as an additional seismic attribute. When estimating attenuation from surface seismics, Q is assumed to be frequency independent. Therefore, another research question we would like to explore is whether Q is frequency independent in the seismic frequency range from our experimental data.

SAMPLE DESCRIPTION

Our limestone samples come from a Middle Eastern carbonate reservoir that is undergoing enhanced oil recovery. Light hydrocarbon production is stimulated by injecting brine into the reservoir (Soroka et al., 2005). The carbonate samples used in these experiments have similar porosity but variable permeability (Table 1), quite characteristic of carbonate reservoirs. We also have a complete petrographical analysis on XRD, SEM, CT-scan and thin sections.

Samples 100 and 200 are mud-supported wackestones with microporosity. Dolomite is present in the vugs or fossil skeletal voids and precipitated after dissolution of calcite. Sample 300 is a packstone boarder-line grainstone with particle porosity and no dolomite content. In all three samples the cement is calcite and there are no clays.

SAMPLE	ϕ (%)	k (mD)	ρ_g (g/cc)
100	32.79	6.8	2.714
200	30.46	21.0	2.714
300	20.39	53.6	2.705

Table 1: Petrographical analysis of the carbonate samples. The porosity (ϕ) and permeability (k) are measured at a confining pressure of 2650 psi and the permeability is corrected for gas slippage (Klinkenberg correction). ρ_g is grain density

The core samples are measured dry (humidified), and 100 % saturated with liquid butane (light hydrocarbon ∼90 API) and high salinity brine (NaCl at 180,000 ppm). Our samples are initially humidified to avoid the softening effect of introducing small amounts of water. We measure from 500 to 4500 psi differential pressure (Pd) for samples 100 and 200, and from 500 to 3500 psi Pd for sample 300. For all rocks the pore pressure was held constant at 500 psi. These pressures are close to the reservoir differential pressure of about 5500 psi. Most of the results presented in this paper are for the highest differential pressure to simulate reservoir conditions.

VELOCITY DISPERSION

Seismic (low) frequencies are obtained between 3 and 3000 Hz, accompanied by a single ultrasonic measurement at roughly 0.8 MHz. A linear fit is applied to the low frequency data to work only with a couple of representative points (3, 100 and 1000 Hz) and have estimates of the variance of the data around the true model assumed to be a line. Details on the uncertainty analysis are presented in Adam et al. (2006). Velocity dispersion is observed from seismic to ultrasonic frequencies.

In visco-elastic materials, velocity increases with increasing frequency. This modulus dispersion is observed for all three samples.The estimated change (dispersion) in the bulk modulus when the rock is saturated with brine from 100 Hz to 0.8 MHz (normalized by data at 100 Hz) is 10% for sample 100, 20% for sample 200, and 38% for sample 300. These numbers indicate a possible positive correlation between dispersion and permeability for these three carbonate samples.

We have information on the P-wave velocity for a well located 1.3 km from the well where sample 300 was cored. The saturating fluid in the formation is a mixture of brine and oil. Because the core does not belong to this well we can only work with an equivalent depth interval, giving a range of velocities rather than a single velocity value. The P-wave velocity in the high permeability interval varies between 3.9 km/s and 4.4 km/s. Figure 1 shows the P-wave velocity from 3 Hz to ultrasonic for sample 300, and the velocity log information is overlaid. Observe that the velocity estimated from different measurement techniques is dispersive. We observe consistency in the behavior of the P-wave velocity for the three frequency intervals, as the frequency increases so does the velocity. Our observations on the velocity dispersion are in agreement to those by the wide frequency range experiment by Sams et al. (1997).

Quite surprisingly, the ultrasonic measurements on the dry samples indicate the presence of dispersion as well. It may be that a small amount of water in the pore space, as the samples are not oven dry, but humidified causes this dispersion. An alternative explanation for this

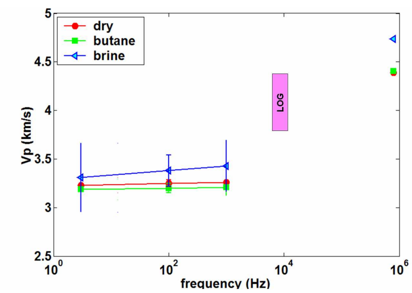

Figure 1: P-wave velocity for sample 300 dry and fully saturated with butane and brine. A nearby well P-wave velocity is compared.

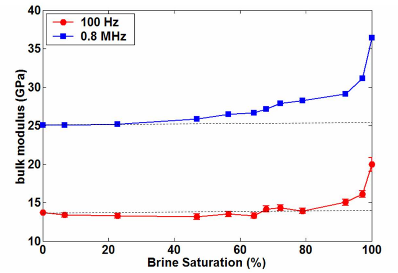

Figure 2: Bulk modulus for sample 300 for different brine saturation

.

unexpected dispersion comes from CT-scan images showing heterogeneity in sample 300, which could create a high-velocity preferential path for the ultrasonic data.

ATTENUATION

For a visco-elastic material we can write the complex elastic modulus $M = M_I + iM_R$, so that the quality factor (Q) can be estimated as $1/Q = M_I/M_R = \tan\phi$ (O'Connell and Budiansky, 1977). This angle ϕ is the phase angle shift between applied stress and resulting strain. In our stress-strain experiment the phase shift is small: $\tan\phi \approx \phi$.

For the ultrasonic data we estimate the attenuation coefficient α by the frequency shift method (Quan and Harris, 1997) and $Q = (\pi f)/(\alpha v)$, where f is frequency and v is velocity. This method statistically models the wavelet frequency spectrum with a Gaussian by integrating the amplitudes over the frequency range. We estimate the compressional and shear wave attenuation for samples 100 and 200, and only the shear wave attenuation for sample 300, due to experimental problems.

Attenuation of seismic waves is sensitive to the saturating fluid as a result of the relative motion of bulk fluids and the rock caused by an applied stress. The influence of pressure is much smaller at typical reservoir and depletion pressures. Quality factors are defined for different deformation or propagation modes: Young or extensional wave, bulk compressibility, compressional and shear waves (Q_e, Q_k, Q_p and Q_s, respectively). For an isotropic rock, only three relations might exist among them: $Q_k = Q_p = Q_e = Q_s, Q_k < Q_p < Q_e < Q_s$, or $Q_k > Q_p > Q_e > Q_s$ (Winkler and Nur, 1979). Which of these relations govern will depend on the saturation state and boundary conditions. If the pore and fluid in the rock are easily compressible, then we expect the bulk compressibility attenuation to dominate. For the shear-wave attenuation to dominate over the bulk compressibility it is assumed that the rock can be modeled with cracks or low aspect ratio pores. Intuitively, this pore geometry means that bulk losses for fully-saturated rocks are smaller than shear losses based on crack-fluid mechanisms (O'Connell and Budiansky, 1977; Mavko and Jizba, 1991).

In carbonates, Lucet (1989) estimated attenuation in the laboratory for 15 limestone samples fully-saturated with water at sonic ($\sim$ KHz) and ultrasonic frequencies. At reservoir pressure and sonic frequencies these samples show larger values of bulk attenuation compared to shear attenuation. Spencer (1981) observed extensional mode attenuation on one limestone sample at seismic frequencies, where the loss mechanism is interpreted to be a reduction of surface free energy in the grains as a result of water, softening the rock.

From the experimental setup and measurements of our limestones we are confident that the samples are 100% saturated with either liquid butane or brine. First we could not get more saturating fluid into the sample for the full-saturation experiment with either butane or brine. Second, Figure 2 shows the influence of brine saturation on the bulk modulus for sample 300. The bulk modulus increases by 20% from 97% to 100% brine saturation. A small amount of gas (on the order of a couple of percent) will drop the bulk modulus to close to dry conditions as we observe in Figure 2. At 100% saturation we observe the significant increase in the bulk modulus which tells us that the rock is fully-saturated, and therefore much stiffer than when dry or partially saturated.

We present the data for bulk compressibility and shear wave attenuation for the three samples and the three saturating fluids: dry (humidified), liquid butane and brine (Figures 3 and 4). We analyze these attenuation modes because their relationship could help on the interpretation whether the losses are dominated by the compressibility of the pores and fluid ($1/Q_k > 1/Q_s$) or by viscous (tangential) stresses ($1/Q_s > 1/Q_k$). Error bars in the plots are one standard deviation of the random error in the estimates of phase and amplitude of the sinusoidal signal. Additional systematic errors can be caused by the system resonances (Figure 3, sample 300). The bulk and shear attenuation at ultrasonic frequency does not show a sensitivity to different saturating fluids as does the low frequency data. For our fully-saturated samples, we observe that $1/Q_k > 1/Q_s$ for all fluids and frequencies. Therefore, the observed attenuation could be explained by losses due to the bulk motion of the fluid and the matrix rather than shear losses. Phenomenologically, the latter one is related to cracks and low aspect ratio pores. This observation is also supported by the petrophysical analysis: the three samples do not show significant evidence of cracks and most of the porosity is intragranular to micritic porosity with rounder pores and vugs.

Our samples remain in the apparatus untouched from dry to butane to brine saturation, the only change is substituting a different fluid into the rock. Overall, the attenuation when the rock is fully-saturated with butane or dry is comparable for each sample, and seems frequency independent. The large difference in attenuation due to fluid is when brine is injected, especially for samples 200 and 300. We are investigating the relatively low attenuation when brine-saturated for sample 100. The changes from butane to brine are of particular interest as this will resemble the enhanced oil recovery process undergoing in the field. We observe that the attenuation can increase a factor of 4 to 10 when the rock is brine-saturated compared to butane-saturated. If time-lapse data is available we might be able to ascertain these large variations in attenuation which are much more significant than typical changes in velocity resulting from fluid substitution (on the order of a factor of 1.15)

As suggested by Spencer (1981), the large attenuation we observe, especially for sample 300, might be explained by the softening of the matrix resulting from the interaction with brine. We have also observed that brine content affects the rock moduli for a partial saturation experiment performed on sample 300. However, the large values of attenuation for sample 300 could also be related to its heterogeneous nature observed in CT-scans.

CONCLUSIONS

One of the potential applications of attenuation for surface seismic analysis is in time-lapse monitoring projects. For these studies, we are interested in changes in the attenuation for different fluids rather than absolute numbers. We can see that the attenuation can increase by a factor of 4 to 10 from a saturating light hydrocarbon to brine at seismic frequencies. This is much larger than usual changes of a factor of 1.15 in the velocity resulting from fluid changes in the reservoir. Estimating attenuation from surface seismic is challenging but we might be able to resolve large changes in attenuation. We also show that for these fully-saturated samples $1/Q_k$ is greater than $1/Q_s$, meaning that the losses are due to the compressibility of the pore space creating a relative movement between the fluid and the matrix. Finally, for these samples we observe that as the sample permeability increases so does the attenuation in the rock.

ACKNOWLEDGMENTS

We thank ADCO and ADNOC for the permission to publish this abstract and the sponsors of the Fluids and DHI Consortia for their support. We thank Kasper van Wijk for his detailed suggestions to this paper. We would also like to acknowledge ExxonMobil URC, where part of the data analysis was performed.

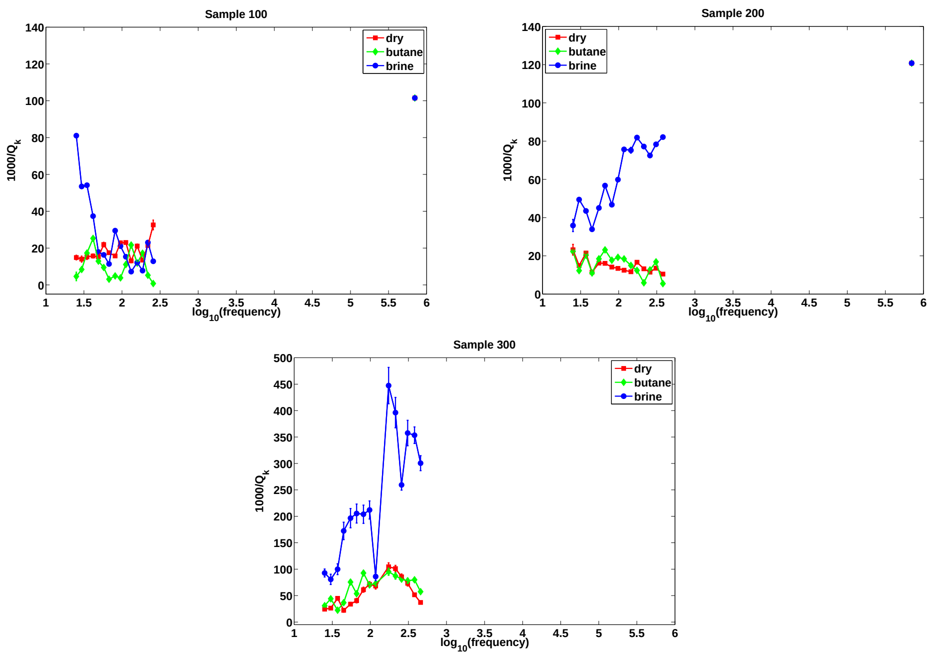

Figure 3: Bulk compressibility attenuation for dry and fully saturated with butane and brine conditions for samples 100, 200 and 300. The differential pressure is 4500 psi for samples 100 and 200, while 3500 psi for sample 300. The plots compare the fluid influence on attenuation as well as the estimated attenuation from ultrasonic data for samples 100 and 200.

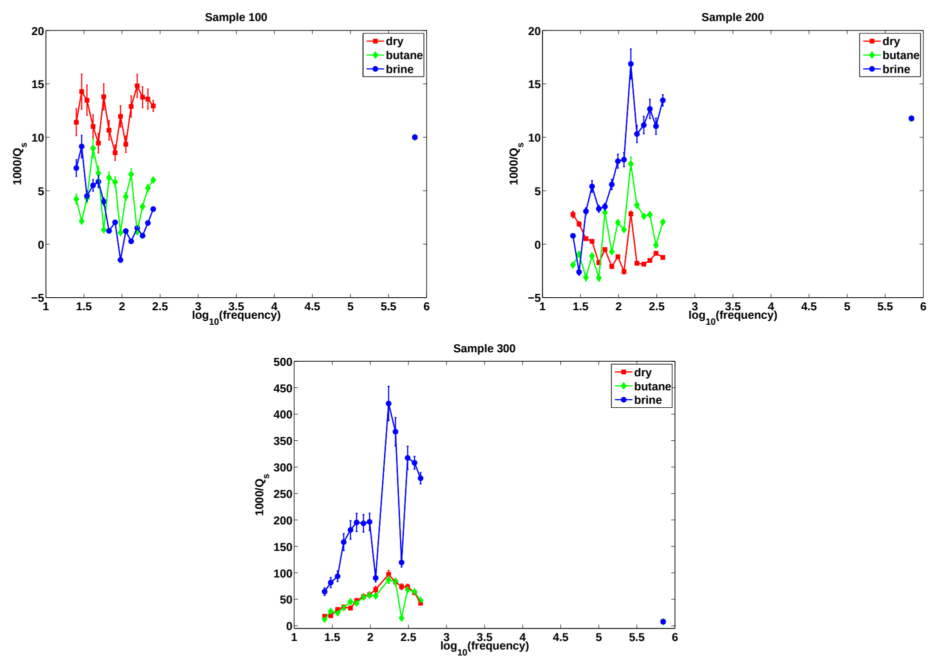

Figure 4: Shear wave attenuation for dry and fully saturated with butane and brine conditions for samples 100, 200 and 300. The differential pressure is 4500 psi for samples 100 and 200, while 3500 psi for sample 300. The plots compare the fluid influence on attenuation as well as the estimated attenuation from ultrasonic data for samples 100, 200 and 300.

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2007 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Adam, L., M. Batzle, and I. Brevik, 2006, Gassmann's fluid substitution and shear modulus variability in carbonates at laboratory seismic and ultrasonic frequencies: Geophysics, 71, no. 6, F173–F183.

Batzle, M. L., D. H. Han, and R. Hoffman, 2006, Fluid mobility and frequency-dependent seismic velocity- Direct measurements: Geophysics, 71, no. 1, N1–N9.

Lucet, N., 1989, Vitesse et attenuation des ondes élastiques et ultrasoniques dans les roches sous pression de confinement: Ph.D. thesis, L'Université de Paris.

Mavko, G., and D. Jizba, 1991, Estimating grain-scale fluid effects on velocity dispersion in rocks: Geophysics, 56, 1940–1949.

O'Connell, R. J., and B. Budiansky, 1977, Viscoelastic properties of fluid-saturated cracked solids: Journal of Geophysical Research, 82, 5719–5736.

Quan, Y., and J. M. Harris, 1997, Seismic attenuation tomography using the frequency shift method: Geophysics, 62, 895–905.

Sams, M. S., J. P. Neep, M. H. Worthington, and M. S. King, 1997, The measurement of velocity dispersion and frequency-dependent intrinsic attenuation in sedimentary rocks: Geophysics, 62, 1456–1464.

Soroka, W. L., P. Melville, E. Kleiss, M. Al-Jenaibi, A. Baker Al-Jeelani, H. H. Hafez, and A. Modavi, 2005, Successful pilot onshore Abu Dhabi shows that 4D can monitor fluid changes in a giant Middle East carbonate field: 75th Annual International Meeting, SEG, Expanded Abstracts, 2430–2433.

Spencer, J. W., 1981, Stress relaxation at low frequencies in fluid saturated rocks: attenuation and modulus dispersion: Journal of Geophysical Research, 86, 1803–1812.

Winkler, K., and A. Nur, 1979, Pore fluids and seismic attenuation in rocks: Geophysical Research Letters, 6, 1–4.