Anisotropic elastic moduli of the Mancos B Shale- An experimental study.

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Summary

Low frequency (0.2-1000Hz) and ultrasonic measurements (800kHz) were performed on the Mancos B shale to determine its elastic stiffness tensor. Measurements were done on core plugs oriented at different angles of symmetry under varying differential pressure conditions. The elastic property of the rock was measured at various frequencies.

Introduction

With the increasing interest in oil shale and shale gas reserves understanding elastic properties of shales have gained prominence. A lot of researchers have investigated into the elastic properties of various kinds of shales and their anisotropy, however not much research has been focused in understanding the frequency dependence.

Kaarsberg *et al.* (1959) performed experimental studies on elastic properties of shales. P-wave velocities were measured in both artificial and natural shale samples in three mutually perpendicular directions as a function of drying time under atmospheric conditions. The samples were tested to be transversely isotropic. Later on studies by Jones and Wang (1981), Lo *et al.* (1986), Johnston and Christensen (1995) all indicate that shales are transversely isotropic in nature. They related the velocity anisotropy in shales to either the preferred orientation of clay minerals or to cracks aligned parallel to bedding at elevated pressures. A very detailed study performed by Vernik *et al.* (1996, 1997) have related velocity anisotropy in shales to thermal maturity and kerogen content. Hornby *et al.* (1996) performed measurements of P-wave and S-wave velocities on two fluid saturated shale samples under drained conditions. Measurements were made on samples cut at 0^o, 90^o and at 45^o to the bedding. Anisotropy values were estimated to be up to 26% and 4% for P-wave and S-wave velocities respectively; and were found to decrease with increasing pressure. Few comprehensive studies have been conducted and published discussing anisotropy in shales.

Wang (2002a, 2002b) published data from 16 shale samples, which showed a strong correlation between P-wave and S-wave anisotropy. He showed that anisotropy decreases with increased pressure and decreased porosity. A comparison of data from experimental study of Wang (2001), with field studies by Sarkar & Tsvankin (2004) showed that anisotropic parameters exhibit frequency dependence. They attributed the variations to the measurement scales. Very few studies have been done comparing the elastic properties of shales over a large range of frequencies. White *et al*. (1983) observed that P-wave velocity from Sonic logs in the Pierre Shale were 6% higher than velocities derived from VSP. Hornby *et al*. (1995) showed that P-wave velocities were much higher from ultrasonic measurements compared to sonic log measurements. Duranti *et al* (2005) performed experiments on shale samples within a wide frequency band (from seismic to ultrasonic band). They observed substantial dispersion effect for some of the elastic properties while some components of the stiffness showed no dispersion at all. They concluded that increasing frequency resulted in increasing stiffness and that more measurements are required to verify the results.

Sample Description

The Mancos "B" shale is an organic rich shale from the Douglas Creek Arch located between the Piceance and Uinta basins in Colorado and is of Cretaceous age. The shale is very thinly laminated with fine grained argillaceous quartz sandstone containing 10% carbonates. The XRD analysis of the shale shows that it is composed of 39% quartz and 33% clay minerals and 17% carbonates. Illite comprises 70% of the clay minerals. The TOC content of the rock is 1.36%. High pressure mercury injection in the Mancos B shale yielded a porosity of 6.6% with median pore throat radius of 0.0148 microns. Vertical permeability and specific storage of this sample varies between 20nDarcy-8nDarcy. Permeability measurements were performed on the shale sample using procedure described by Sarker et al., 2009.

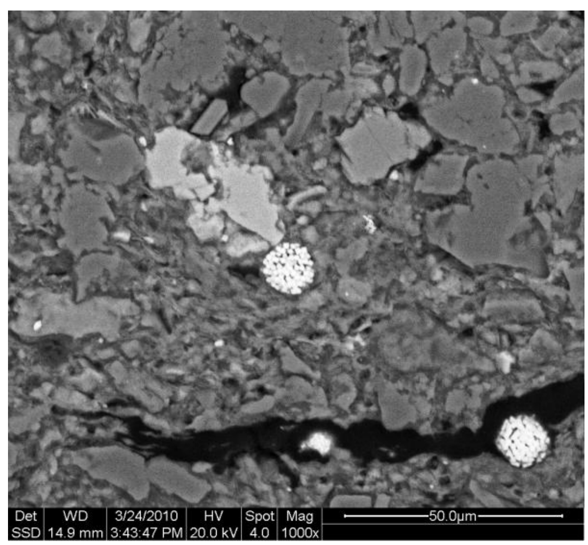

Figure 1: Back scatter SEM image of Mancos B shale showing clay rich and silt layers. The matrix is composed of mainly illite quartz and carbonates with occasional pyrites framboids. The dark matters indicate organic matter present in the clay.

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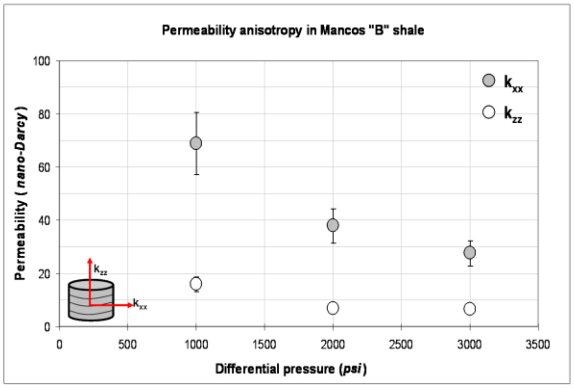

Figure 2: Permeability anisotropy in Mancos B shale with decane as pore fluid. Confining pressure was kept constant at 4000psi.

Sample Preparation

Three different core plugs cut at 0°, 45 ° and 90° with respect to the symmetry axis was used for the experiment. Both ultrasonic transducers for velocity measurements and strain gages oriented at various directions were mounted on the sample to allow estimation of stiffness at both ultrasonic and low frequencies simultaneously under similar conditions.

Detailed descriptions of sample preparation technique and gage mounting for transversely isotropic materials have been provided by Hoffman, 2005. We used similar techniques for our low frequency sample preparation. To expedite the diffusion process the sample is injected with pore fluid from the two ends. The pore fluid is then lead to a wire screen attached to the sample surface by means of grooves cut on a lexan end piece which was sandwiched between sample and the aluminum transducers.

Experimental Procedure

Measurements were done at various levels of confining and differential pressures. Pore pressure was kept constant at 500psi for the saturated samples throughout the experiment. We allowed pore fluid equilibration time of about 36-48 hours for each change of confining pressure. Static strain measurements were done at an interval of 5-6 hours to ensure that pore pressure was equilibrated inside the sample. The experiment was a loading experiment where the differential pressure increased at all times to ensure there was no hysteresis effect on the measured compliances. Decane was used as the pore fluid because of its nonpolar nature. Most polar compounds easily react with the swelling clay in the shales and alter the internal macrostructure which is not desirable.

We conducted ultrasonic and low frequency measurements on the transversely isotropic Mancos B shale. In case of TI symmetry, the rock has five independent elastic compliances S_{11} S_{12} S_{13} S_{33} S_{44}. The general form is:

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\\ \varepsilon_5\\ \varepsilon_6\end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0\\ S_{12} & S_{11} & S_{13} & 0 & 0 & 0\\ S_{13} & S_{13} & S_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & S_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & S_{44} & 0\\ 0 & 0 & 0 & 0 & 0 & S_{66}\end{bmatrix}\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{bmatrix}$$

Where ε_i is the strain, S_{ij} is compliance tensor and σ_{ij} is the stress, all in the reduced notation. Procedure for low frequency measurement technique has been described by Batzle *et al.* (2006). A complete description of the low frequency setup and measurement and analysis procedure for transversely isotropic materials has been discussed in Hofmann (2005). A similar approach was taken to measure elastic properties of the transversely isotropic Mancos B shale sample, using the Low Frequency device uniquely available at the Colorado School of Mines.

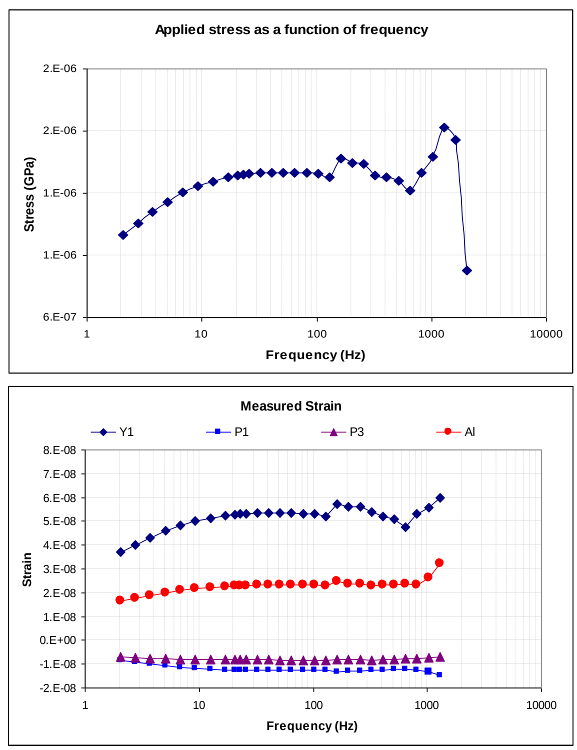

Figure 3: a) Applied stress for Mancos Shale at θ=90°, b) Measured strain on Mancos B Shale at θ=90°.

Three different core plugs cut at 0°, 45 ° and 90° with strain gages mounted at various angles were used for determining the low frequency compliance tensor components. For Ultrasonic measurements, the single-plug (90^o core plug) lab-based technique described in Wang (2002) was applied to the Mancos B shale. An example of the applied stress and the measured strain on the 90^{o}shale is shown in Figure 3.Y1 is the Young's gage , Al is the gage mounted on the Aluminum end piece and P1, P3 are Poisson's gages that are mounted on the 90^o sample. Arrangement of the various strain gages on the three different cores has been discussed in Hoffman (2005).

From the strain measured with strain gage put on the Aluminum end piece (transducer) the applied stress is estimated and is used to calculate compliances. With the current configuration we estimated the compliances S_{11}, S_{12}, S_{13} and S_{66} from the core cut at θ= 90^o, S_{44} and S_{33} from the core cut at θ= 45^o and S_{33} from the core cut at θ= 0^o at various levels of differential pressures. We have used S_{33} estimated from the θ= 0^o core as the S_{33} estimated from the θ= 45^o core is very noisy.

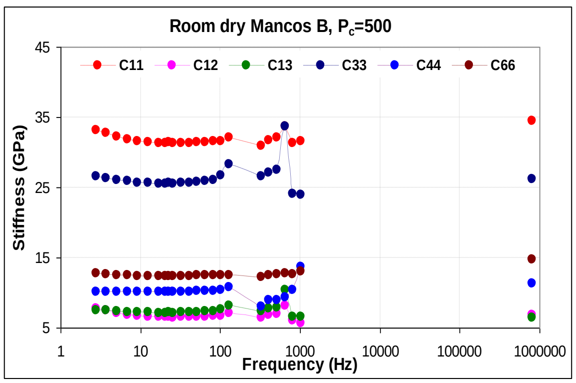

Figure 4: Estimated stiffness for room dry sample at P_d=500psi as a function of frequency from 2Hz-800 KHz.

The compliance tensor is then inverted to obtain the stiffness tensor. Stiffness components for the room dried shale at a differential pressure of 500psi are shown in Figure 4. The slight increase in the ultrasonic stiffness components is well within the experimental error limits and hence can not be considered as a frequency effect. Similar effects are seen for the saturated samples at P_d=1000psi and P_d=2500psi. For both cases pore pressure was kept constant at 500psi (Figure 5). However, if carefully noticed, significant pressure effects can be seen on the C_{11} and C_{33} components. C_{11} and C_{33} both increase with increase in differential pressure.

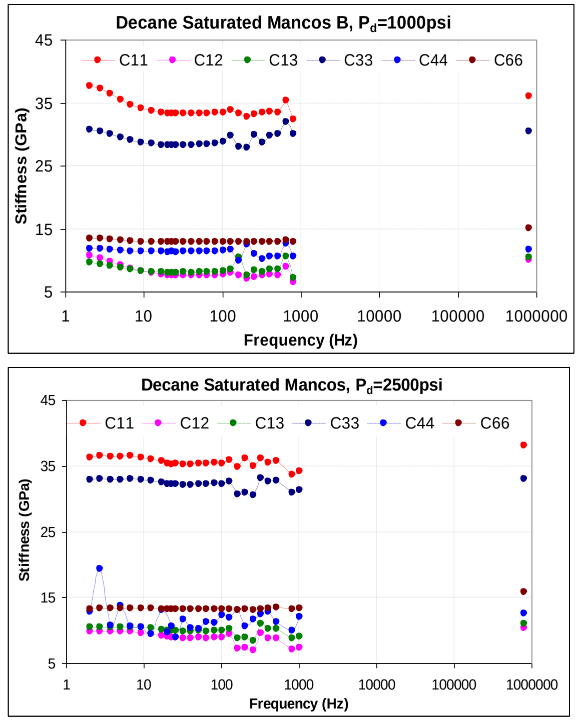

Figure 5: Estimated stiffness for decane saturated sample at P_d=1000psi and P_d=2500psi respectively as a function of frequency. P_p was kept constant at 500psi.

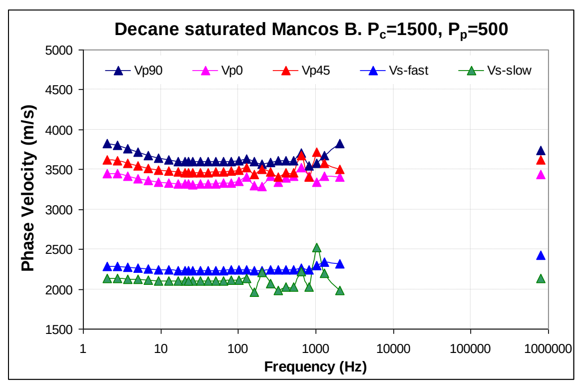

Figure 6: Estimated phase velocities for decane saturated sample at P_d=1000psi.

Observations and Conclusions

Under saturated conditions the Mancos B shale exhibits P-wave anisotropy of about 9% and shear wave anisotropy of about 5%. Measurement of permeability in the two principal directions show a permeability anisotropy of about 4, which reduces with increasing differential

pressure. The stiffness components as well as phase velocities are pressure sensitive specially C11 and C33.
Both C11 and C33 increase with increasing differential pressure. However no significant change is observed for the shear components C66 and C44 under saturated conditions. C33 is most sensitive to pressure changes indicating presence of micro-cracks which close due to increasing differential pressure. No significant dispersion effect is seen in the estimated stiffness components or the phase velocities estimated for the Mancos B shale. The reason to this could be the low porosity of the shale (~7%). Similar effects were seen by Hoffman *et al*, 2005 for their low porosity West African Shale. They had reported significant dispersion of the stiffness components for higher porosity shale. The cause of this may be attributed to fluid related effects. More measurements need to be done on higher porosity shale to confirm this idea. It should also be kept in mind that the strain measurements are point measurements and hence are likely to be influenced by the heterogeneity of the sample (silt and clay layers) and hence the stiffnesses computed could be the property of individual elements.

Acknowledgements

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