Oil shale anisotropy measurement and sensitivity analysis

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Summary

We have measured velocity anisotropy on 13 core samples from an organic shale oil reservoir with differential pressure up to 3000 psi. The pressure effect on velocities is generally stronger in direction normal to the bedding than along the bedding, and thus the anisotropy decreases with increasing differential pressure. P-wave anisotropy and vertical *Vp/Vs* ratio have good correlation with TOC content: the higher is the TOC content, the stronger is P-wave anisotropy and the lower is *Vp/Vs* ratio. The measured P-wave anisotropy is generally greater than S-wave anisotropy. Sensitivity of c_{13} and δ to errors in velocity and angle measurement were analyzed. From the sensitivity analysis we conclude that both the angle and velocity measurement around 45^o are critical for reliable anisotropy measurement.

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Equipment

The bench top equipment(Fig. 1) is used for quick anisotropy measurement under low stress conditions. An air compressor (maximum output air pressure 100 psi) is used to applied uniaxial pressure for better coupling between transducers and sample. Both P-wave and S-wave velocities can be measured at the same time. By changing the position of samples three times, all the velocities required for VTI anisotropy calculation can be acquired on one horizontal core plug. The uniaxial stress can be turned off and on instantly with a switch and make it very easy to unload or change positions of the sample. So this method is time-saving and very cheap, and also it is not very strict on sample size and shape.

To measure the stress effect on anisotropy, we use the anisotropy measurement equipment designed by Yao and Han(2005). Using this system, in situ reservoir pressure and temperature conditions can be applied. For this system, only one horizontal core plug with diameter of 1-1/2 inch is needed for VTI anisotropy measurement.

Sample description

There are totally 13 core plug samples from a shale oil reservoir. Half of the samples appear oily in black color, the other samples appear calcareous with gray color. The porosity are in range of 1 to 5%, however the bulk density vary in a wide range from 2.24 g/cc to 2.66 g/cc. Oily samples have low bulk density (< 2.4 gm/cc) in comparison with high bulk density of calcareous samples (> 2.6 g/cc). All measurement are on “as received” saturation condition. All core samples are in cylindrical shape with its central axis parallel to the bedding (as shown in Fig. 2). Only 2 of the 13 samples have diameter of 1-1/2 inch and were measured on both equipment introduced earlier, the other 11 samples with diameter of one inch were measured only on bench top equipment.

Data analysis

Figures 3 and 4 shows the velocity anisotropy

Figure 1: Bench top ultrasonic measurement equipment

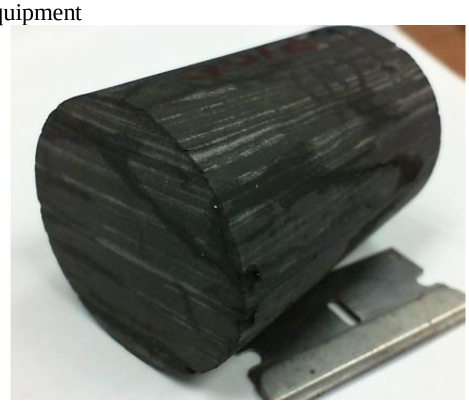

Figure 2: Sample #1 (horizontal plug)

measurement data. Notations here generally follow the rock physics handbook by Mavko, et. Al. (1998). The data point at 90 psi is measured on bench top. The velocity data from different equipment generally follow the same trend and have good agreement. So the bench top equipment can be used for quick anisotropy measurement. It can be seen that generally the pressure has stronger effect on the velocity normal to the beddings(V_{P0}) than velocity parallel to the beddings(V_{P90}). The P-wave velocities have much steeper

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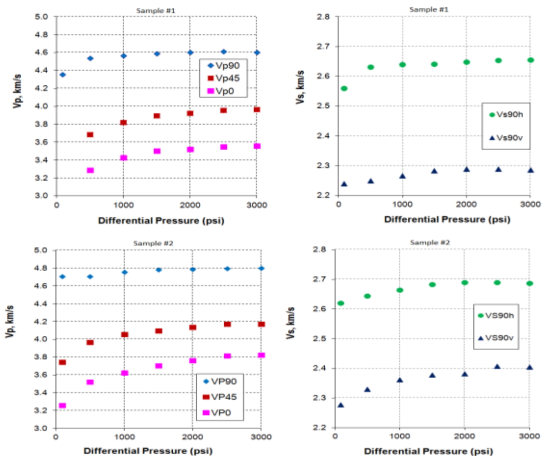

Figure 3: Anisotropy velocity measurement data of two oil shale core samples (Data points at 90 psi are measured on bench top)

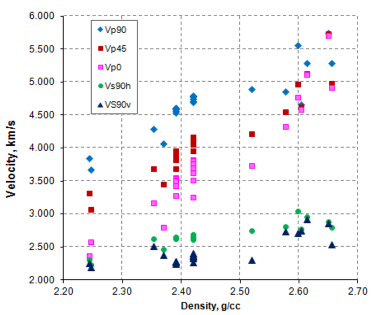

Figure 4: Anisotropy velocity measurement data for all the samples, the two samples shown in Figure 3 have bulk density close to 2.40g/cc

trend of increasing with bulk density than S-wave velocities.

Figures 5, 6 and 7 show the calculated VTI elastic moduli and Thomson anisotropy parameters. Of the five elastic moduli, c_{33} and c_{13} show stronger pressure influence than c_{44} and c_{66}. From the measurement, anisotropy parameter ε is much larger than γ and δ, and decreases significantly with increasing differential pressure; anisotropy parameters γ and δ are not sensitive to differential pressure. Parameter δ is small and close to zero, but is unstable at low differential pressure, which may due to high sensitivity to measurement error. c_{13} shows strong pressure dependency and even decreases to negative value at low differential pressure. From Figure 6, the P-wave related elastic constants (c_{11}, c_{33} and c_{13}) have much steeper trend of increasing with bulk density than S-wave related elastic constants. Figure 7 shows the crossplots of Thomson anisotropy parameters with bulk density. It can be seen that there is good correlation between ε and bulk density, but the correlation between bulk density with γ or δ is poor. This is due to two factors: first the bulk density (or TOC) indeed has stronger influence on ε, and secondly, measurement of γ and δ have higher error bar because they are related to shear wave velocities and/or V_{P45}. Figure 8 shows the correlation between c_{13} and P-wave anisotropy (ε). Negative c_{13} occurs for core samples with strong P-wave anisotropy ($\varepsilon>0.4$). Some of these samples broke along the bedding surface during measurement on bench top. Thus the negative value of c_{13} might be caused by open fractures along bedding interfaces under low pressure.

As Vernik and Milovac(2011) pointed out there is good correlation between TOC content and bulk density. All the samples we measured content carbonate minerals. The total organic content (TOC) of these samples are not measured. The organic matter has much lighter density (around 1.2 g/cc) than calcite and clay, which are other two primary components in the shale matrix with similar mineral density of 2.7 g/cc. In addition, all the samples have low porosity of 1 - 5%, so that the density differences of these samples are primarily controlled by TOC content. The lower is the bulk density, the higher is the TOC content. Figure 9 shows the correlation between bulk density and *Vp/Vs* ratio at direction normal to the bedding. Under same pressure, the *Vp/Vs* ratio has a clear trend to increase with bulk density, which is due to increasing calcite and clay content(both minerals have K/μ ratio bigger than 2.0). After correction of pressure effect, the low *Vp/Vs* ratio of 1.6 is good indicator for high TOC shale, which is consistent with the result reported by Vernik and Milovac (2011).

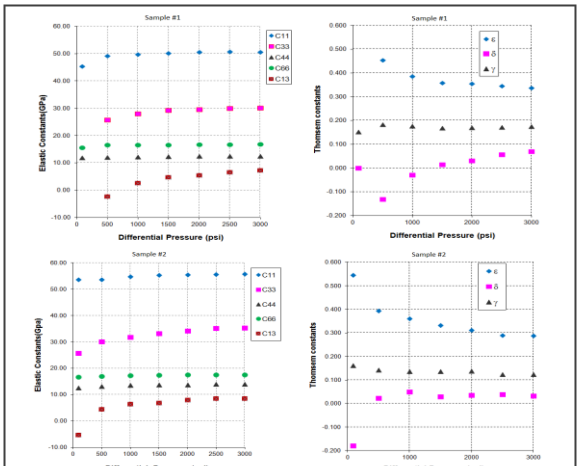

Figure 5 Elastic constants and Thomson parameters of sample #1 and sample #2

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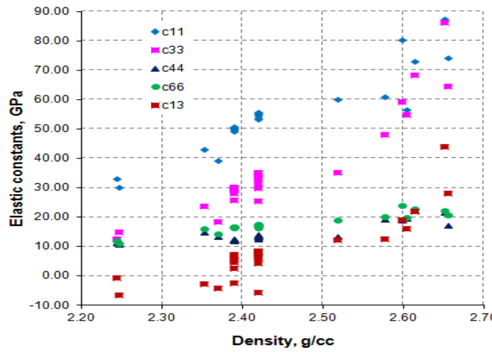

Figure 6 Relation between bulk density and VTI anisotropic constants

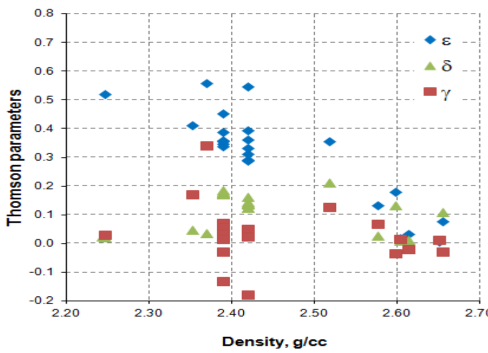

Figure 7: Relation between bulk density and VTI elastic constants

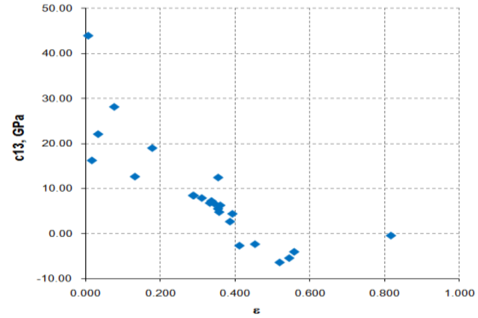

Figure 8: Correlation of c_{13} with P-wave anisotropy (ε) (13 samples, same for Fig. 7 and Fig. 8)

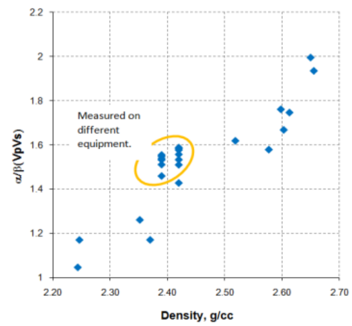

Figure 9: Correlation between Vp/Vs ratio (normal to bedding) and bulk density

Sensitivity analysis

All the sensitivity analysis in this study are based on measured parameters of sample #2. The P-wave velocity at 45^o (V_{P45}) to the bedding is used to estimate c_{13} because of the simple formulation:

$$c_{13} = \sqrt{\left(c_{11} + c_{44} - 2\rho V_{P45^o}^2\right)\left(c_{33} + c_{44} - 2\rho V_{P45^o}^2\right)} - c_{44} \qquad (1)$$

Figure 10 and Figure 11 show sensitivity of c_{13} and δ to velocity measurement. Each time only one velocity component is perturbed. From Figure 9, c_{13} is most sensitive to measurement error on V_{P45}. 1% of V_{P45} error can cause 40% error in c_{13}. Usually shear wave velocity has bigger uncertainty than P-wave velocity because the shear wave signal is often contaminated by converted P-wave signal. So S-wave velocity can also cause significant error in c_{13}. Figure 11 shows sensitivity of δ to velocity measurement. It can be seen that δ is extremely sensitive to measurement error on V_{P45}. Over or under estimation of V_{P45} by 1% can change the signal of δ. Unlike c_{13}, δ is not sensitive to the measurement error in shear velocity.

c_{13} can also be estimated using P-wave velocity in any direction not normal or along the bedding using the formulation:

$$\begin{aligned} &c_{13} = \csc(2\theta)\left(2\sqrt{D} - c_{44}\sin(2\theta)\right), \\ &D = \left(c_{11}\sin^2\theta + c_{44}\cos^2\theta - \rho V_{P\theta}^2\right)\left(c_{33}\cos^2\theta + c_{44}\sin^2\theta - \rho V_{P\theta}^2\right) \end{aligned} \qquad (2)$$

Where $V_{P\theta}$ is the P-wave velocity at angle θ with normal direction of the bedding. When $\theta = 45^o$, equation (2) is simplified to equation (1). Equation (1) is often used to calculate c_{13} when the P-wave velocity is measured at angle not "far" from 45^o by assuming it will not introduce significant error.

To analyze the sensitivity of c_{13} and δ to angle error we assume that the actual angle at which V_{P45} is measured lies between 40^o to 50^o. Then we use equation (2) to calculate corresponding values for c_{13}, and calculate δ using updated c_{13}. Comparing with those values calculated using equation (1) when 45^o is assumed, from Figure 11, there is significant difference: error of 5^o can cause over 50% error

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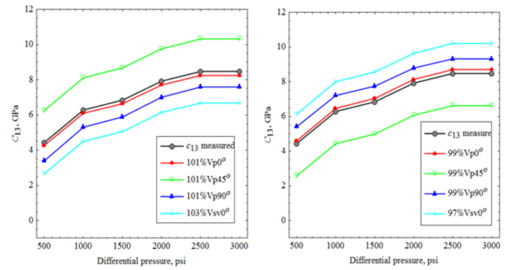

Figure 10: Sensitivity of C_{13} to velocity measurement error(101% means overestimated by 1% and 99% means underestimated by 1%, each time only one velocity is perturbed, same for Fig. 10)

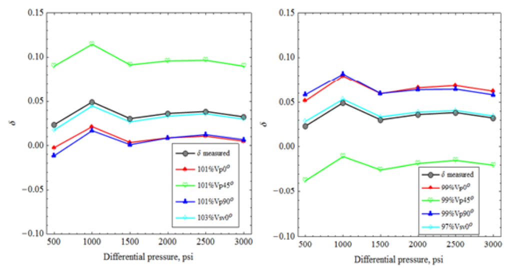

Figure 11: Sensitivity of δ to velocity measurement error

in estimation of c_{13} and sign change of δ. When three core samples (0°, 45° and 90°) are used for anisotropy measurement, making of 45° core plug is often challenging and angle error of *5°* is not rare. So that when the angle is not exactly 45°(with error bigger than 1°), we should use equation (2) to calculate c_{13}. One should be very careful in interpreting the physical meaning of δ from the anisotropy measurement data.

Figure 13 shows how angle error affects prediction of angle dependent quasi-model velocities. Comparing with Thomsen (1986) and Berryman (2008) approximations (Figure 14), the prediction error introduced by angle error in V_{P45} can be much more significant than the error introduced by the Thomsen or Berryman approximations.

Conclusions

Bulk density of the organic shale, which has good correlation with TOC, has significant influence on P-wave anisotropy(ε) and *Vp/Vs* ratio normal to bedding. The *Vp/Vs* ratio can be a good indicator of high quality organic shale(*Vp*/Vs<1.6). The angle and velocity measurement around 45° is critical for reliable anisotropy measurement.

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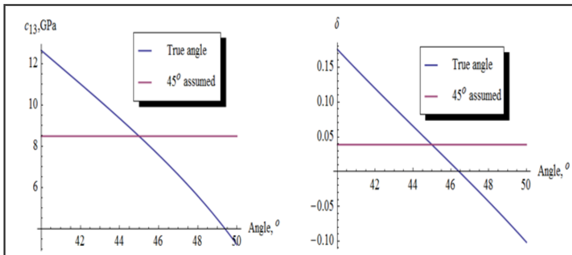

Figure 12: Sensitivity of c_{13} and δ to angle error(-5° to +5°) when 45° is assumed(based on sample #2 at differential pressure of 2500 psi, same for the following figures)

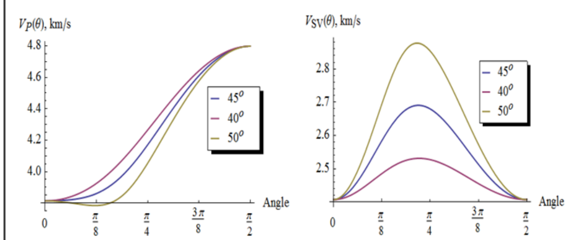

Figure 13: Sensitivity of quasi-mode wave velocities to angle error(-5° or +5°) when 45° is assumed.

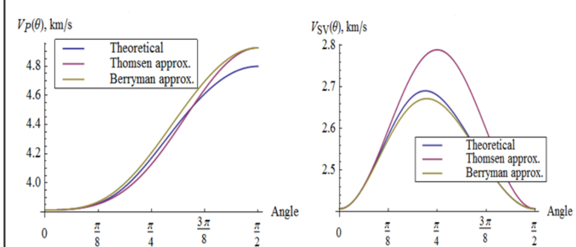

Figure 14: Comparing of theoretical quasi-mode wave velocities with Thomsen and Berryman approximations. The error introduced by angle inaccuracy(Fig. 13) might be much bigger than the approximation errors.

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EDITED REFERENCES

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