Acoustic properties of coal from lab measurement

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Summary

Ultrasonic velocities, densities and porosities for a set of coal and surrounding silty coal, silty shale, and shaly coal samples were measured in laboratory. The pressure effect, temperature effect, and saturation effect on velocities and anisotropy were evaluated. The results were compared and correlated with the well log data and discrepancies were analyzed. The potential influences of the coal seams to neighboring gas or oil reservoir seismic response were discussed.

Introduction

Coal is the most abundant fuel source currently known on the earth. The worldwide recoverable coal resources are estimated around 1 trillion tons. In addition, all coals contain some amount of coal bed gas. The preliminary worldwide coal bed gas resources are estimated from 164 to 686 trillion cubic meters. Its economic significance requires that we have a thorough understanding of the physical, chemical and petrophysical properties of the coal; among these, the acoustic properties are essential for exploration and production of coal and coal bed gas.

The study of the diagenesis-coalification process of coal reveals that the coal formation is frequently associated with the generation of other hydrocarbon resources (Diessel, 1992). It can be the source rock for gas and oil, which implies the possible proximity of coal formation to oil or gas reservoirs. The special acoustic properties of the coal formation, e.g., low velocity and low density, cause large impedance contrasts between coal seams and interseam sediments, thus a strong reflection is expected from the single boundary of coal formation. However, a detailed study (Hughes 1983) revealed that a strong cyclic sequence of bedding, with thin coal seams interleaved with thicker layers of shale or sandstone layers, will allow a large amount of energy be transmitted through the system but with its first arrivals slightly delayed. The amount of delay and apparent attenuation of the seismic wave is frequency dependent. Figure 1 from Hughes (1983) demonstrates how the multiples within the coal seams affect the synthetic reflection seismic signal. The proper modeling of this kind of phenomenon and its impacts on seismic interpretation also requires an accurate knowledge of the acoustic properties of the coal.

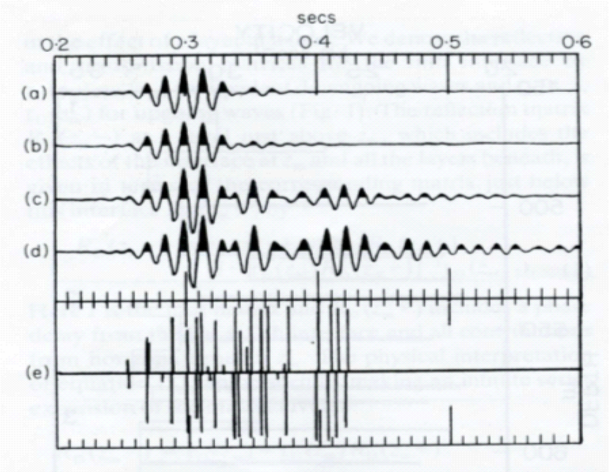

Figure 1. Synthetic seismic reflection from cyclic coal seams.

Sample preparation

We have received 9 “less-than-half” vertical slab cores, and managed to cut and polish them to obtain 7 1.5” plugs for ultrasonic measurement. Table 1 is a summary of those plugs. It includes the sample number, well name, depth, lithology, porosity, water saturated density, and water saturated ultrasonic velocity measured under 200 bar differential pressure. VP0 is the compressional wave velocity propagating perpendicular to bedding, and VS90v is the shear wave velocity propagating along the bedding,

Sample	Well	Depth_lo	Depth_up	Litho	Rho_sat	Porosity	VP0	VS90V
		m	*m*		*g/cc*	*%*	*km/s*	*Km/s*
772	A	2578.84	2578.90	Coal ?	1.73	4.9	2.56	1.25
765	B	2745.58	2745.69	Coal	1.37	4.7	2.32	1.22
766	B	2745.88	2746.00	Shaly Coal	1.38	7.4	2.41	1.13
770	C	3063.66	3063.79	Silt Shale	2.85	14.7	3.76	2.05
771	C	3064.53	3064.66	Coal	1.36	12.0	2.43	1.09
769	C	3065.33	3065.44	Silty Coal	1.63	N/A		1.15
768	C	3068.44	3068.59	Coal	1.44	11.1	2.42	1.08

Table 1. Summary of the samples measured in laboratoty

with polarization perpendicular to bedding. Assuming a VTI media, this is equivalent to the shear wave velocity propagating perpendicular to bedding.

Porosity

The porosities of sample 768, 771 were measured by He_2 porosimeter, and sample 772, 770, 765, 766 were calculated by injected water (for saturation) divided by bulk volume. No porosity for sample 769 value was obtained due to the bad shape. The porosity values for all samples range from 4.7% to 14.7 %.

Ultrasonic velocity measurement

For coal samples (765, 766, 768, 771, 772), we measured 5 component velocities under "as is" and "water saturated" condition with a differential pressure range from 50 to 200 bar. For silty coal (769) and shale (770) samples, only pressure effect on Vp and Vs were measured. In Figure 2, we plot the water saturated velocity against the density. It is very clear that lithology is the first order factor to separate both the density and velocity of coal from surrounding shale. The scattering within the coal is probably caused by the mixture of coal with other minerals. Referring to table 1, we can identify the two samples with density above 1.5g/cc. One of them is #769 categorized as silty coal; the other one is #772 which, although categorized as coal (by sample provider), showed obvious shale content interleaved within the core sample. The abnormal higher anisotropy of this sample (discussed later) is also an evidence of its interlayering structure.

Pressure effect

Figure 3 plots the pressure effect for all water saturated samples. In our experiment range the coal samples do not exhibit strong pressure sensitivity. The typical velocity increase is 1.97% to 3.83% for Vp, and 2.68% to 7.28% for Vs, when pressure increases from 50 to 200 bar. By comparison, the shale sample (770) exhibits a relatively large pressure effect, wherein Vp increased 12.24% and Vs increased 29.10%. The basic matrix framework of coal comes from organic plant and does not have the granular structure of other minerals like sandstone and shale. Thus, any effective media theory based on granular contact model is not appropriate to interpret the pressure effect on coal.

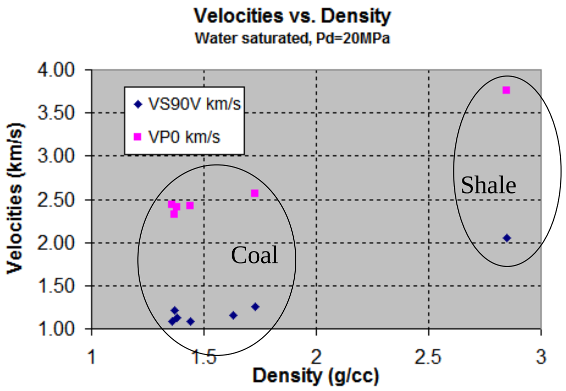

Figure 2. Velocity and density are well separated into coal and shale groups.

Anisotropy

The coal intrinsically has anisotropy due to its cleat structure (Warwick, 2005). From five component velocity measurements (Yao and Han, 2005), we calculated the Thomsen parameters for all samples except #769 due to the difficulties to obtain Vp0 and Vp45. The P and S anisotropy are displayed in Figure 4a and Figure 4b. All five coal samples exhibit strong velocity anisotropy. P wave anisotropy is larger than shear wave anisotropy. Generally, the anisotropy for water saturated samples is not sensitive to increasing pressure. However, we also measured and computed the anisotropy for samples before water saturation, and found they not only have higher values but also have higher pressure sensitivity (Figure 4c). While we see that the intrinsic anisotropy for coal and shale has similar values in these plots, we also observed an

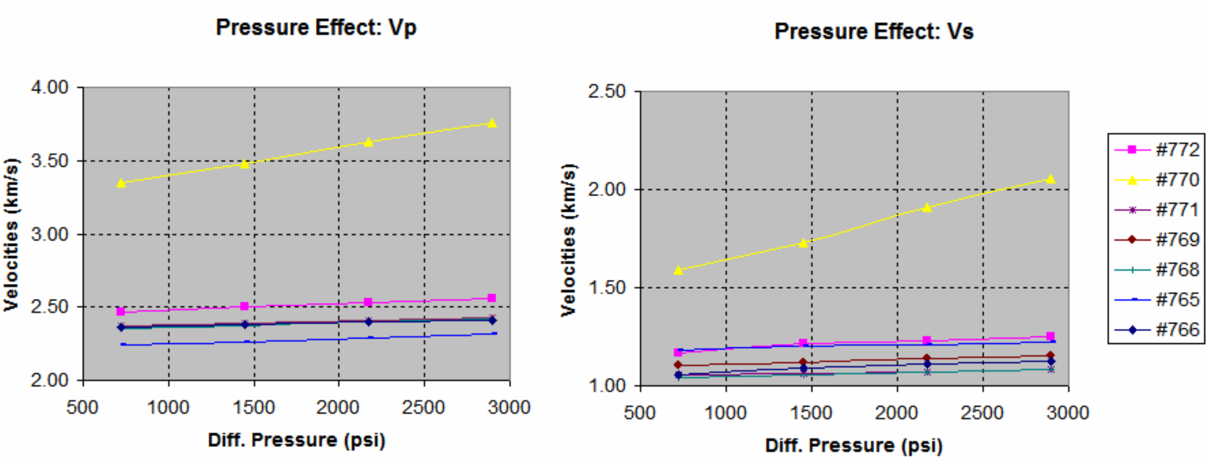

Figure 3. Coal samples are less sensitive to pressure change compared with shale sample.

extremely high value for sample # 772. By visual checking the plug, we found several layers of shale with the thickness of mm scale. So there is additional layering anisotropy contributing to this abnormal high value.

Temperature effect

Most of the measurements were made at room temperature, but the reservoir temperature was reported to be around 90^{o}C. To evaluate the possible temperature effects, we measured one water saturated sample (771) with changing temperature from 22^{o}C to 90^{o}C, and then returning to 23^{o}C to check the repeatability. The resulting velocities and derived Thomsen anisotropy parameters are displayed in Figure 5a and 5b. The plots show that this temperature increase will cause more than a 15% velocity decrease for Vp90, Vs90, and an 8% decrease for Vp0 and Vp45. The trends are almost linear in the experimental temperature range. This provides a guideline for possible correction on core and well data correlation. Figure 5b shows that the intrinsic anisotropy of coal is significantly reduced with increasing temperature. It suggests that the coal anisotropy is caused by certain ordered structures with preferred alignment in one direction. When temperature increases, those structures tend to become more disordered and thus lose their directional preference.

Saturation effect

Both “as is” and “water saturated” velocities were measured and compared. Figures 6a and 6b plot the water saturation effects on velocity and anisotropy for sample #768. Other coal samples exhibit similar results. From those results, we concluded that water saturation of the coal sample will significantly increase P wave velocity, slightly reduced S wave velocity, and significantly reduce the anisotropy.

Lithology heterogeneity

Thin coal bedding can be laminated with shale or mudstone at a very small scale (several mm). With some of the provided samples, we can hardly obtain a single lithology plug, thus the measurement results can vary depending on the transducer position. One such example is the sample

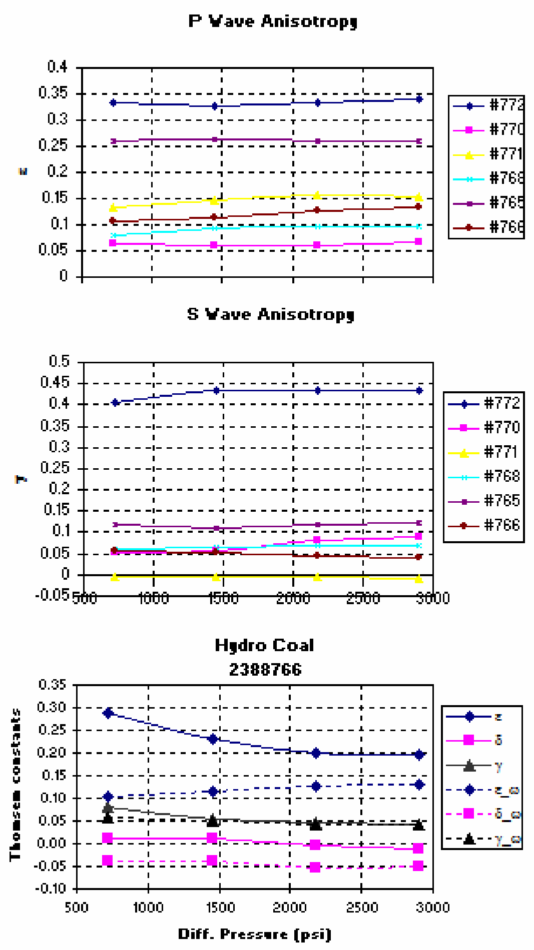

Figure 4. Anisotropy of all samples. a) P wave anisotropy b) S wave anisotropy c) Before water saturation, anisotropy has a larger value and higher pressure sensitivity.

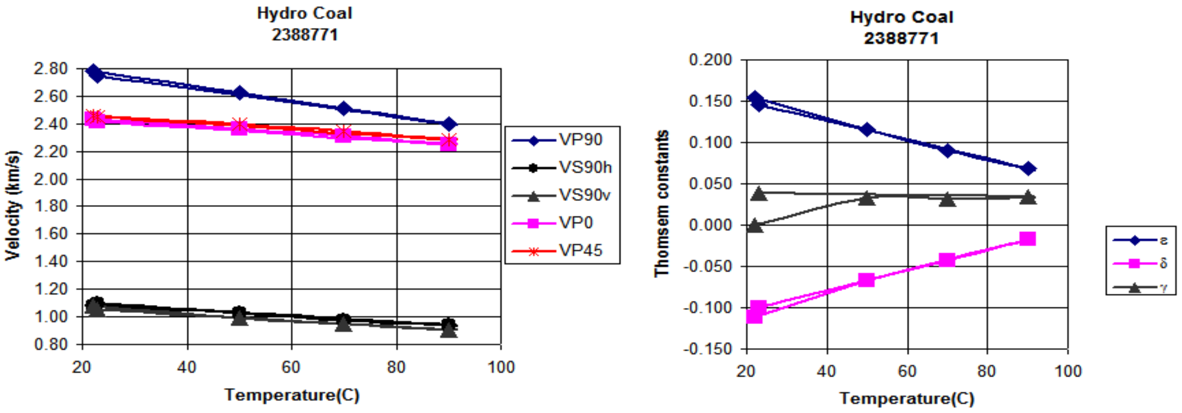

Figure 5. Measured temperature effects on water saturated coal sample. a) Velocities b) Anisotropy

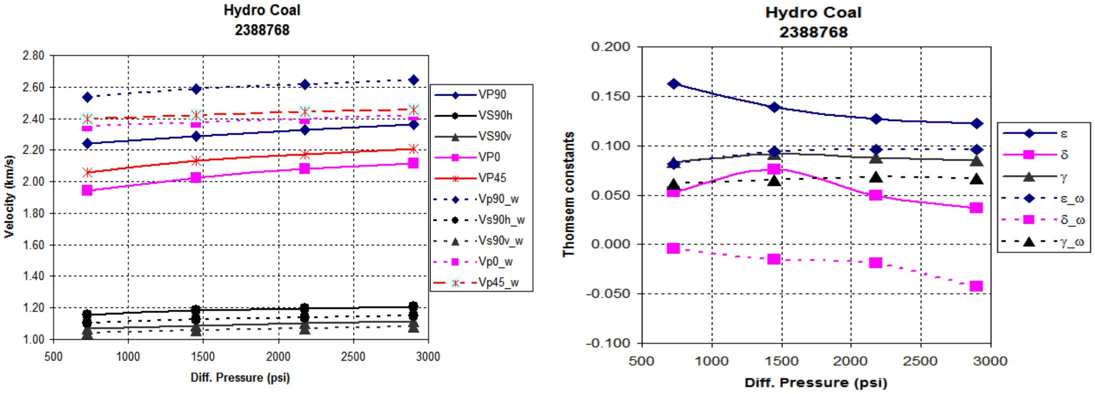

Figure 6. Measured water saturation effects on coal sample. a) Velocities b) Anisotropy

772. The bulk density value 1.68g/cc is neither a typical value for coal, nor for the shale, which indicates that the plug is a mixture of coal and shale. The very high Vp90 suggests a shale velocity. while the Vp0 and Vp45 values are much closer to small coal values. Similarly, the Vs90h and Vs90v also show very large differences, which cannot be explained with normal anisotropy. Measurement of effective properties at a large scale may be more dominated by the low end member coal properties.

Correlation with well log

After applying certain core depth correction and well log KB adjustments, the core data can locally tie with the logging in all three wells for Vp vertical and bulk density Figure 7 shows the correlation on Well C. The locations of the coal layers are further indicated by other measurements like Neutron porosity log, which has abnormal high value due to high Hydrogen content in coal. The remaining discrepancies can be ascribed to several factors:

1. Logging resolution is lower than core measurement, and thus tends to smooth out the large heterogeneity observed from core;
2. Core depth correction information is not complete, and may not be the same for each core sample;
3. The exact temperatures at the core depth for the 3 wells are not available. Temperature correction of core velocities can bring them down as much as 8%.
4. There is a dip angle between bedding normal and the well. Thus the sonic Vp should be neither Vp0, nor Vp90. For well C, we estimate the dipping angle to be about 37 degrees. Using the full elastic tensor obtained from our 5 component velocity measurements, we can calculate the Vp and Vs at any angle. The results show that Vp at 37 degree is very close to Vp0 (less than 0.7% difference). So as first order approximation, we just correlate the Vp0 with well logs.

Conclusion

The ultrasonic measurement of coal samples reveals that coal has strong intrinsic anisotropy. Its velocities and anisotropy are not sensitive to pressure changes up to 200 bar. However, both the velocity and anisotropy are very sensitive to water saturation and temperature change. The highly cyclic sequence of coal seams and other formations at a very small scale (high heterogeneity) bring issues to core-well tie which require special attention and treatment. It also impacts the interpretation of seismic responses from nearby oil or gas reservoir. The lab measurement of key properties on the coal samples will help to address the above issues. More lab work and integration of other data are needed to serve those purposes.

Acknowledgement

The coal core samples used in this study were provided by Hydro. We also thank Hydro for allowing us to show the results.

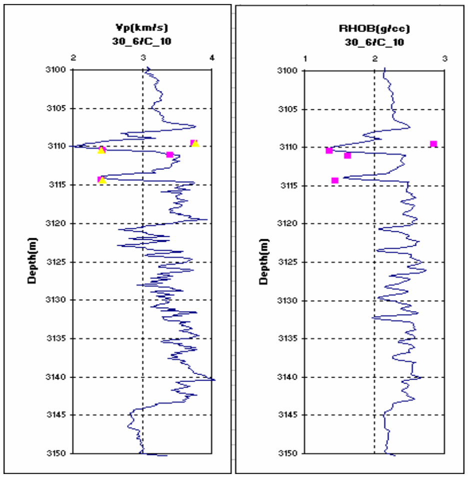

Figure 7. Correlation of measured vertical P wave velocity and density to well log data.

EDITED REFERENCES

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