

## Seismic characterization of kerogen maturity: An example from Bakken shale

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### Summary

The conversion of kerogen to oil/gas will build up overpressure. Overpressure is caused by conversion of solid kerogen to fluid hydrocarbons in a relatively fixed pore space. The excess pressure caused by kerogen maturity does have impact on the seismic elastic properties. The wave propagation, velocities, anisotropy and AVO effects by kerogen maturation have been obtained as a function of initial kerogen content (immature), excess pore pressure (mature) for Bakken shale from Williston basin, USA. Our analysis show that more matured shales are brittle and suitable for hydraulic fracturing for maximum production.

### Introduction

Thermal maturity of source rock measures the degree to which a formation has been exposed to high heat needed to break down the organic matter to generate hydrocarbons. Source rock maturity yields oil/gas which develops overpressure (e.g., Meisner, 1978; Luo and Vasseur, 1996). It is important to understand how the maturity of kerogen will affect the seismic properties that are of interest to geophysicists. Immature source rocks are in the normal pressured regime and the pressure increases with maturity and over-matured source rocks will be in over-pressured regime (Figure 1).

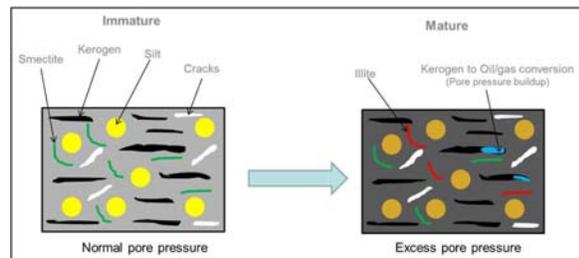


Figure 1: Comparison between an immature and mature source rock.

Source rock maturity also yields additional cracks. Smectite to illite transition due to maturity also generate some free water in the formation. It is important to understand how the over-pressure caused by source rock maturation will affect the seismic properties.

### Simple model for kerogen maturity (Carcione, 2000)

An immature source rock is considered as a viscoelastic transversely isotropic medium containing illite (clay) and kerogen (Figure 2). Illite is treated as transversely isotropic (TI) and kerogen as an isotropic medium. As the seismic wavelength is much larger than the thickness of the individual (illite/kerogen) layers, the medium behaves as a homogeneous, TI material whose stiffnesses can be calculated from Backus averaging (Schoenberg and Muir, 1989). When the kerogen to oil/gas conversion exceeds the rate of volume loss due to fluid flow, excess pore pressure is generated. The excess pore pressure can be estimated as a function of converting factor (Berg and Gangi, 1999). As the kerogen maturity increases, Kuster and Toksoz (1974) model is used to calculate the bulk modulus and density of the oil and kerogen mixture.

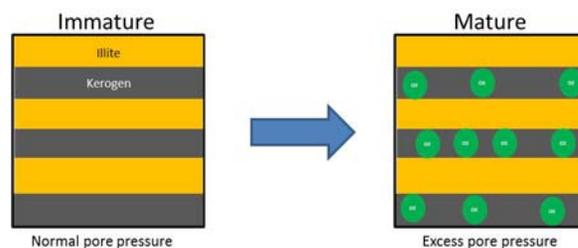


Figure 2: Schematic representation of kerogen maturity

### Example: Bakken shale

We used the published ultrasonic and kerogen content information from Vernik and Nur (1994) for Bakken shale from Williston basin, USA. It is estimated that around 10 to 400 billion barrels of oil have been generated from Bakken shales and charged both conventional and unconventional plays in the basin (Jin et al., 2012). The source type of Bakken shale is mainly type I/II.

Figure 3 shows the published TOC (wt%) and bulk density values (filled blue circles) for Bakken shale. We calculated TOC from bulk densities of rocks, and densities of kerogen and illite. The best fit (open circles) line is obtained when TOC accounts for approximately 22% of kerogen.

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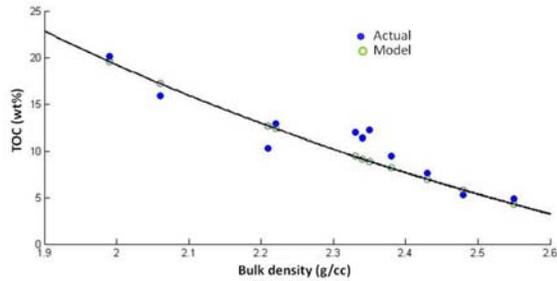


Figure 3: Relation between density and TOC for samples of Bakken shale.

### Elastic properties of immature Bakken shale

Experimental and calculated phase velocities (both  $V_p$  and  $V_s$ ) are plotted with kerogen in the Figure 4. Both  $V_p$  and  $V_s$  decrease with increase of kerogen content. The difference between the model and experiment may be due to mineral composition. The actual Bakken shales may have other minerals such as quartz and calcite. But our model considers only illite (70%) and initial immature kerogen (30%) of each rock sample.

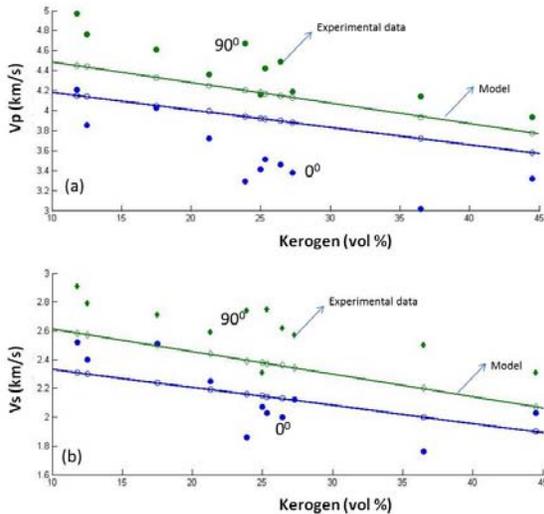


Figure 4: Bedding parallel ( $90^\circ$ ) and bedding perpendicular ( $0^\circ$ ) velocities for (a) compressional wave and (b) shear wave

Figure 5 shows the Thomsen anisotropic parameters calculated from the experiments.

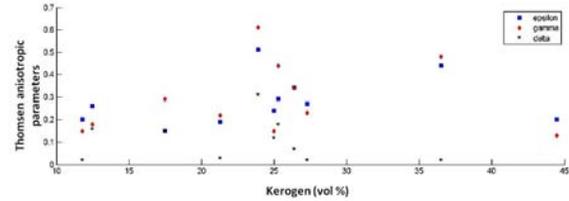


Figure 5: Thomsen's anisotropic parameters derived from the experiments

### From immature to maturity of Bakken shale

As the source rock matures, the solid kerogen starts to transform to liquid oil. When this transformation happens in a relatively fixed pore space, excess pore pressure is generated. This excess pore pressure also generates micro-cracks which will act as conduits for the fluids to migrate.

The depth of Bakken shale varies from 3000 to 3400m in the study area. The lithostatic pressure ( $=\rho z g$ ) at a depth of 3.2km ( $z$ ) for an average density of 2.4 g/cc ( $\rho$ ) is equal to 75 MPa, where  $g$  is acceleration due to gravity. The hydrostatic pressure is equal to 31 MPa. So, the maximum possible pore pressure change ( $\Delta p$ ) will be from hydrostatic to lithostatic, i.e., nearly 44 MPa. At this excess pressure, the rock may reach the fracture stage.

The initial content of kerogen is considered as 30%. A fraction of it changes due to maturation and kerogen to oil conversion generates excess pore pressure. This excess pressure is calculated based on Berg and Gangi's (1999) relation. The amount of excess pressure generated due to kerogen conversion is shown in the Figure 6a. About 35% of initial kerogen of 30% has to be converted to oil to generate fracture pressure of 44 MPa.

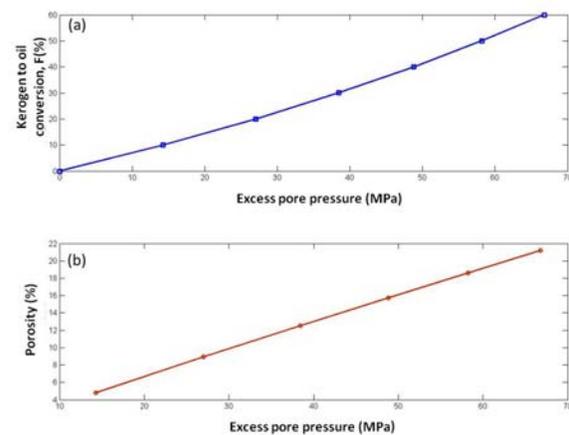


Figure 6: Fraction of kerogen converted to (a) oil and to (b) porosity with excess pore pressure

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Kerogen conversion also increases the porosity. If we consider the initial porosity as the initial kerogen proportion  $K$ , the porosity increases from this value to  $K_{exp}$  ( $C_p \Delta p$ ). Figure 6b shows the fraction of kerogen converted to porosity with excess pore pressure. The porosity increase at the fracture pressure (i.e. 44 MPa) is around 14% of the initial porosity.

The bulk, shear moduli and density of kerogen and oil composite is calculated using Kuster and Toksoz (1974) spherical inclusion model. These values are used to derive the complex stiffness elastic moduli and wave phase velocities have been derived (see Carcione, 2000). Wave velocities with excess pore pressure are shown in the Figure 7. Both  $V_p$  and  $V_s$  decrease with the increase of excess pore pressure.

Figure 8 shows the anisotropic parameters with excess pore pressure. The anisotropy increases with the pore pressure due to kerogen to oil conversion.

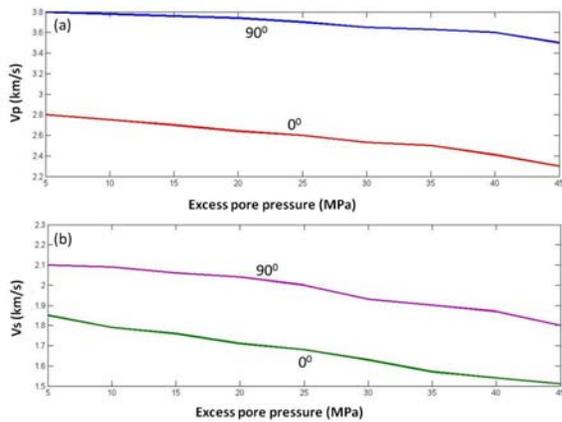


Figure 7: Bedding normal ( $0^\circ$ ) and bedding parallel ( $90^\circ$ ) velocities for (a) P-wave and (b) S-wave, versus excess pore pressure, for an initial kerogen content of 30%.

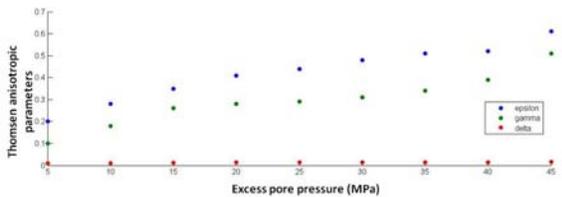


Figure 8: Thomsen's anisotropic parameters with excess pore pressure.

### Effects of kerogen maturity on wave propagation and AVO

We plotted the wave propagation for P,  $S_v$  and  $S_h$  waves by treating as VTI medium. For immature Bakken shale, we considered the velocities and anisotropy parameters for initial kerogen 30% (Figure 9 a&b). We considered the velocities and anisotropic parameters when the excess pore pressure reached 44 MPa (Figure 9 c&d). It is observed that the maturity affects the wave propagation.

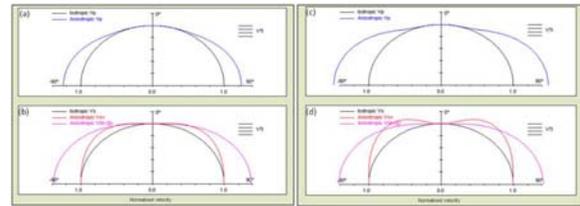


Figure 9: Anisotropic wave propagation for Bakken shale for (a) immature P (b) immature  $S_v$  and  $S_h$  (c) mature P and (d) mature  $S_v$  and  $S_h$  waves.

We also computed the affects of maturity on AVO (Amplitude Variation with Offset). Mississippian Bakken shale is overlain by Lodgepole limestone formation in the Williston basin. The Lodgepole formation is considered to be isotropic and its properties are,  $V_p=5.28$  km/s,  $V_s=2.81$  km/s and density= $2.5$  g/cc (Bandyopadhyay, 2009). Shuey's (1985) two term approximation is used to calculate the P wave reflectivities for both immature and mature Bakken shale (Figure 10). For immature, it's a typical class IV AVO. The reflective amplitude increases from immature to mature as shown in the figure.

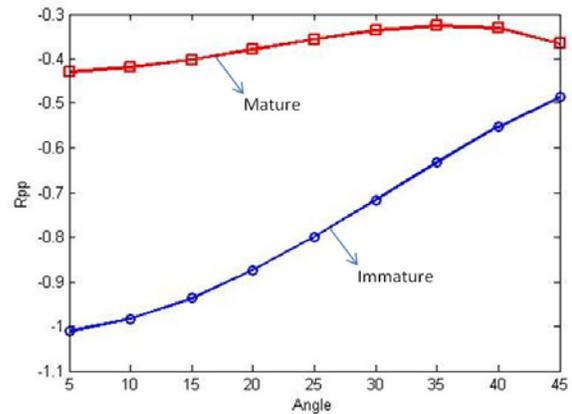


Figure 10: Variation of PP reflectivity for mature and immature Bakken shale.

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## Effects of kerogen maturity on geomechanical properties

Hydraulic fracturing is necessary for production from the shale. Hydraulic fracturing is successful for more brittle shale rocks. The concept of brittleness combines seismic derived properties such as Young's modulus ( $E$ ) and Poisson's ratio ( $\nu$ ). These two explain the rocks ability to fail under stress ( $E$ ) and maintain a fracture ( $\nu$ ), once the rock fractures (Rickman et al., 2008). Higher acoustic impedance ( $I_p$ ) also indicates brittleness. It is important to understand how the TOC and kerogen maturity will affect the geomechanical properties of shales. Higher Young's modulus and lower Poisson's ratio indicate that the rock is more brittle and prone for fractures after hydraulic fracturing. Brittleness index can be simplified as the ratio of these two parameters ( $=E/\nu$ ) (Guo et al., 2012).

Figure 11 shows the cross plots between Young's modulus and Poisson's ratio (Figure 11a) and between acoustic impedance and Poisson's ratio (Figure 11b). The low TOC shales are more brittle. The cross plot between brittleness index and hydrogen index also confirm that more matured and low TOC shales are more brittle and suitable for successful hydraulic fracturing.

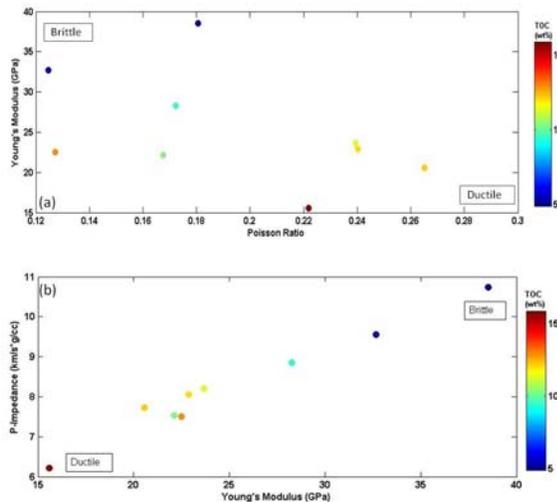


Figure 11: Cross-plots between (a) Young's modulus and Poisson's ratio (b) P-impedance and Young's modulus, color coded with TOC.

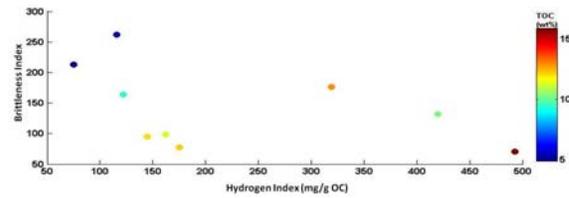


Figure 12: Cross-plot between brittleness index and hydrogen index, color coded with TOC.

## Conclusions

It is deduced from this study that the kerogen maturity will affect seismic properties. The properties of matured shale are expressed in terms of excess pore pressure. P and S wave velocities decrease and anisotropy increases with the increase of kerogen maturity. The wave propagation of elastic waves (especially P and Sv waves) is affected by kerogen maturity. AVO is also changed by maturity. Immature Bakken shale has class IV AVO and its amplitude is affected by kerogen maturity. More matured shales have high brittleness thus suitable for hydraulic fracturing for optimized production.

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#### EDITED REFERENCES

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