Static and Dynamic Properties of the Bakken

Jesse Havens and Michael Batzle
Department of Geophysics

Summary

Ultrasonic velocities and static moduli have been measured on four samples from the middle Bakken and one sample from the upper-bounding Lodgepole limestone for the purpose of calculating the minimum horizontal stress. In Facies C and D moderate anisotropy has been observed, and is consistent with bedding-parallel microcracks modeled with Hudson’s crack model. Facies E showed negligible anisotropy even though the sample contained strong visible layering and high clay volume. Bedding sub-parallel microcracks suggested by Pitman et. al., 2001 could cause the observed anisotropy, but the intrinsic anisotropy of crystalline calcite has probably added to this effect. A sample from Facies C or D with high dolomite volumes should be measured to test this hypothesis (the samples here had trace amounts of dolomite).

The static moduli have been interpreted as weakening at the grain contacts. The dry laboratory measurements from this study and the data from Vernik and Nur, 1993 have been fluid saturated with Gassman’s equation to replicate the relaxed fluid response in the static domain. By and large the high frequency stiff fluid response is inappropriately applied when modeling horizontal stress. The results show a reduction in the anisotropy parameters, and for large porosities a dip in horizontal stress is observed when going from the isotropic to anisotropic equations.

The relative horizontal stress can be evaluated between the shales and middle Bakken through AVO analysis. Ambiguity will exist because intrinsic anisotropy and horizontal fractures will drive the anisotropy higher, but as horizontal fractures increase so will the fracture porosity driving the anisotropy parameters down. But even if we completely disregard the mechanisms involved, the AVO response should give a strong indication of the horizontal stress contrast between the shales and middle Bakken. If the far-offset data has high amplitudes, then the horizontal stress contrast will be large. The desired stress contrast should be locally determined.

The Bakken Shales

The Bakken shales exhibit transverse isotropy (Vernik and Nur, 1992) and have been studied extensively (Vernik and Nur, 1993; Vernik, 1994a; Vernik, 1994b, Vernik and Liu, 1997). In this project we did not have sufficient core plugs to measure the anisotropic static moduli; therefore we will opt to build a model based on previous experimental data from Vernik and Nur, 1993.
The data from Vernik and Nur, 1993 has been adjusted in the following study for reasons that will not be fully explained here. The basic motivation for altering the data was because both a quasi-compressional and quasi-shear velocity was measured, allowing two independent calculations of the material properties. There are strengths and weaknesses to both velocity types, and those were taken into account when deciding on the most representative material properties.

The data from Vernik and Nur, 1993 is shown in Figure 1. The Thomsen anisotropy terms (Thomsen, 1986) are plotted against the vertical Vp/Vs ratio. Most of the data is from dry samples at 70MPa confining pressure, but there is also a 5MPa sample included. The crack-free estimate determined by linear extrapolation is shown in black, whereas the actual data points are in red. Assuming there are horizontal microcracks open at low stress, I can estimate the crack density with Hudson’s crack model (Hudson, 1981). This is a two-step process since the Hudson crack model requires an isotropic background. The first step is to remove the intrinsic anisotropy by considering only the vertical velocities (in black). Then adjust the crack density until the stiffness coefficients match the red points. Next, simply add the intrinsic and crack generated anisotropy parameters to get the effective anisotropy. For the data shown here the crack density is 0.051. Notice the Vp/Vs ratio differentiates between high intrinsic anisotropy and high anisotropy due to microcracks.

![Figure 1: The vertical Vp/Vs ratio versus the epsilon and delta anisotropy parameters. The black points connected to the red points are ‘crack-free’ estimates of a sample measured at 5MPa](image-url)
confining pressure. The red points are the actual measurements assumed to contain intrinsic and microcrack-induced anisotropy.

The data in Figure 1 should not be directly applied to horizontal stress calculations. This data is from dry samples, and will not accurately represent the relaxed static moduli necessary for horizontal stress calculations. To approach the static domain, the fluid response should be modeled with Gassman’s equation. The anisotropic equation is given in Mavko and Bandyopadhyay, 2009. The resultant anisotropy parameters are all decreased, and the amount of decrease depends on the porosity of the sample. In a heavily fractured zone, it is likely that the anisotropy causes a drop in horizontal stress rather than an increase. Since the matrix porosity of the Bakken shale’s is generally ~1% much of the porosity measured in a well log could be related to microcracks or fractures. The Vp/Vs ratio and porosity can be used to distinguish between intrinsic and fracture/microcrack induced anisotropy. Then the horizontal stress can be estimated by modeling the data with Hudson’s crack model for dry cracks and saturating the sample with Gassman’s equation.

The Middle Bakken and Lodgepole

Anisotropic velocities were measured in Facies C, D, and E. In Facies C no oblique angle velocities were taken, but symmetry plane velocities necessary to calculate the anisotropy parameters epsilon and gamma are available. The anisotropy in Facies E was negligible, and may be considered isotropic. The anisotropy in Facies C and D were not insignificant; for brevity I have reported the anisotropy parameters for Facies D in Figure 2. Unlike the Bakken shale, the anisotropy parameters have the inequality delta > epsilon, which is the predicted response of dry cracks by Hudson’s model. As a comparison, Backus Averaging (Backus, 1962) models anisotropy due to fine layering and predicts near elliptical anisotropy (delta = epsilon). If subparallel microcracks are assumed to be the cause, then the missing anisotropy parameter delta can be modeled with Hudson’s crack model for Facies C.
Figure 2: The Thomsen anisotropy parameters versus confining pressure. At low stress delta is greater than epsilon, and as stress is increased delta and epsilon approach each other. This is a typical response for bedding-parallel microcracks.

The static moduli are interpreted as a weakening of the grain contacts due to the change in strain amplitude. For the isotropic samples I have introduced surface coupling factors that can be explained through the model by Sayers and Kachanov, 1995. The purpose is to have a multiplying factor to quickly compare the static and dynamic moduli. The most comprehensible values occur if I use the stiffness coefficients. For an isotropic medium I only need two:

\[ C_{11} = \rho V_P^2 \]  
\[ C_{44} = \rho V_S^2 \]  

The surface coupling factors are then derived in such a way that

\[ C_{11}^{\text{STATIC}} = m C_{11}^{\text{DYN}} \]  
\[ C_{44}^{\text{STATIC}} = n C_{44}^{\text{DYN}} \]

The averaged values for all pressures are given in Table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>m</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies F</td>
<td>0.91</td>
<td>0.89</td>
</tr>
<tr>
<td>Facies E</td>
<td>0.95</td>
<td>0.59</td>
</tr>
</tbody>
</table>
The approximate changes in static moduli are now easy to understand. The compressional stiffness changes similarly for all the samples. The shear stiffness changes much less in Facies F than the other two samples. I have not interpreted why this might occur, but I assume the grain surfaces have a significant role (roundedness, roughness, etc.).

The anisotropic samples cannot be directly converted to all the stiffness coefficients since not all the necessary engineering terms were measured. I may be able to apply an effective medium to estimate the missing terms or assume the surface coupling factors are similar to the ones already measured.

**AVO Analysis**

The AVO response can also help in determining general horizontal stress profiles. The linear approximation given by Ruger, 1997 can be utilized to determine the change in delta over the interface between the upper Bakken shale and the middle Bakken. In Figure 3 the Bakken shales and middle Bakken have high positive deltas. In Figure 4 the middle Bakken delta is now slightly negative. Since there is a higher contrast in Figure 4 the amplitude of the reflections is higher with increasing offset (blue indicates highest offset). This may help determine fluid pathways or locate highly fractured zones. To a first order the horizontal stress can be approximated by assuming the isotropic equation (vertical velocities) and adding the delta term, so given the vertical velocities one can also estimate the horizontal stress contrast. This may be useful when deciding drilling strategies.

*Figure 3: Synthetic seismic for the Bakken interval. The last major trough and peak are the regions of interest. In black is the 0° incidence, red=10°, green=20°, and blue=30°. In this example the shales and middle Bakken have positive deltas.*
Interpreting the AVO response will not be an easy task, but this is a possible opportunity to acquire more than geologic structure from the seismic data.

Conclusions

- Anisotropy measured in the middle Bakken Facies D is consistent with dry bedding-parallel microcracks
- The vertical Vp/Vs ratio can be combined with porosity to estimate intrinsic versus fracture-induced anisotropy
- Conversion from dynamic to static moduli can be easily done with surface coupling terms
- The AVO response of the Bakken shale/middle Bakken interface can help model the horizontal stress contrast on a large scale

Acknowledgements

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References


Mavko, G., Bandyopadhyay, K., Approximate fluid substitution for vertical velocities in weakly anisotropic VTI rocks, Geophysics, 74, D1-D6.

