Microstructure characterization and S-wave velocity prediction in the Barnett Shale formation

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SUMMARY

Microstructure characterized by pore aspect ratio is a critical parameter which reveals the connectivity of fluid-filled cracks and pores and therefore has a strong influence on permeability in shales. Pore aspect ratio also has a great effect on elastic properties. We use the self-consistent approximation method to build a shale rock physics model for the inversion of pore aspect ratio. Inverted results show that the value of aspect ratio presents much less variety in the Barnett Shale compared to that in surrounding carbonates, which may imply the presence of more complex systems of fractures and cracks in the surroundings. We then investigate the correlations between geomechanical properties and microstructure parameters, and find that the increase in crack density decreases Young's modulus and shear modulus in surrounding carbonates but such correlation is not obvious in the Barnett Shale. In addition, the effect of crack density on Poisson's ratio is weak in all the relevant formations. Another work of this study is to predict S-wave velocity by using the inverted aspect ratio as a constraint. The prediction results indicate good agreements between predicted and real S-wave velocity for all three tight formations.
Introduction

Microstructure characterization is critical for the economic production of shale gas. Due to very low porosity and permeability in shales, pore geometry characterized by aspect ratio becomes a critical parameter which reveals the connectivity of fluid-filled cracks and pores, and therefore has a strong influence on permeability in shales (Vernik et al., 2012). Also, previous study indicates that pore aspect ratio has a greater effect on elastic properties compared to porosity (Guo et al., 2012). In this study, our objective is to build a shale rock physics model for the inversion of pore aspect ratio, and then investigate the correlations between geomechanical properties, mineralogy, aspect ratio, and crack density. Another work in this study is to predict S-wave velocity by using the inverted aspect ratio as a key constraint parameter. The proposed methods are applied to the Barnett Formation.

Data description

Figure 1 illustrates well logs of the Barnett Formation. The Barnett Shale is overlaid by the Marble Falls and underlaid by the Ellenburger, and is ready to be recognized by higher gamma ray values and lower velocities and density compared to the carbonate surroundings. Porosity in the Barnett Shale is higher compared to that in the surroundings. Poisson's ratio in the lower Barnett Shale is much higher than that in the upper Barnett Shale. Geochemical well logging indicates that mineralogical constituents of the Barnett Shale are complicated, comprising clay, quartz, carbonates, and pyrite. Elastic properties of each kind of mineral to be used in rock physics modeling are given in Table 1 (Mavko et al. 2009).

Methodology

The effective medium theory we use in this study is the self-consistent approximation (SCA) method given by Berryman (1980). The method provides the estimate of self-consistent elastic modulus $K_{SC}^*$ and $\mu_{SC}^*$ of rocks given $n$ phases of mineralogy and pore-space:

1. $\sum_{j=1}^{n} f_j \left( K_j - K_{SC}^* \right) \beta_j^* = 0,$

2. $\sum_{j=1}^{n} f_j \left( \mu_j - \mu_{SC}^* \right) \zeta_j^* = 0,$

Each $j$ indicates a phase of mineralogy or pore space with a corresponding volume fraction $f_j$ and bulk ($K_j$) and shear ($\mu_j$) modulus. The factors $\beta_j^*$ and $\zeta_j^*$ describe the geometry of an inclusion.

Figure 2 (a) demonstrates workflows and associated effective medium theories in our rock physics model. Because low porosity and very low permeability in the Barnett Formations prevent hydraulic communication and pore-pressure equilibrium, the SCA method as a high-frequency model is suitable...
for obtaining moduli of the tight rocks in this study. Figure 2 (b) illustrates a calculated template in terms of P-wave velocity and porosity crossplotting for the Barnett Shale. Each solid line corresponds to a constant mean value of pore aspect ratio $\alpha$ which has a statistical normal distribution. Three cases of $\alpha = 0.01, 0.1,$ and 1 are highlighted with schematics and histograms. As illustrated in Figure 3, the purpose of the inversion is to estimate $\alpha$ for each data point overlaid on the template, and the criterion is to find the best match between the $V_p$ observed in well logs and the $V_p$ predicted by the SCA method for a specific porosity. We can also use $V_s$ to predict $\alpha$ by conducting similar procedures. Therefore, scattering relations between $V_p$ and $\phi$ can be explained by the variation in pore geometry $\alpha$.

Figure 4 (a) illustrates the value of $\alpha$ inverted from $V_p$ (blue) and $V_s$ (red), respectively. We find that the value of $\alpha$ presents much less variety in the Barnett Shale compared to that in surrounding formations. This may imply the presence of more complex systems of fractures and cracks in the surrounding carbonates, because compared to shales, they are more easily eroded and fractured during the process of deposition and diagenesis. The evaluation of fractures in the surroundings is also critical before hydraulic-fracturing. Figure 4 (c) displays the derived crack density (Mavko et al. 2009), which is a combined measure of both pore shape in Figure 4 (a) and porosity in Figure 4 (b):

$$\varepsilon = 3\alpha / 4\pi \phi$$

(3)

We can see that the Barnett Shale presents relatively higher crack density due to higher porosity compared to the surrounding formations.

**Microstructure characterization**

In Figure 5 and Figure 6, we investigate the relation between mineralogy and geomechanical properties, and the relation between mineralogy and microstructure parameters in the Barnett Shale.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m$^3$)</th>
<th>Bulk modulus (GPa)</th>
<th>Shear modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>2650</td>
<td>37</td>
<td>44</td>
</tr>
<tr>
<td>Pyrite</td>
<td>4810</td>
<td>147</td>
<td>133</td>
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<tr>
<td>Calcite</td>
<td>2710</td>
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<td>32</td>
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<tr>
<td>Dolomite</td>
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<td>45</td>
</tr>
<tr>
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<td>25</td>
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<tr>
<td>Oil</td>
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<td>0</td>
</tr>
<tr>
<td>Water</td>
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<td>2.25</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 1 Material properties**

(References in Mavko et al. 2009)

**Figure 2** (a) A diagram showing effective medium theories used in our rock physics model. (b) A rock physics template for the Barnett Shale, showing constant lines of aspect ratio calculated by the SCA method. Schematics and histograms of three scenarios for pore aspect ratios with normal distributions are also shown.

**Figure 3** A crossplot of P-wave velocity versus porosity in the Barnett Shale. Solid lines indicate constant aspect ratios calculated using the SCA method.
In Figure 5, we can see that the increase in clay content decreases Young's modulus $E$, while the increase in quartz content reduces Poisson's ratio $\nu$. In Figure 6, however, the relations of mineralogy with $\varphi$, $\alpha$, and $\varepsilon$ are not obvious. In Figure 7, we find that $\varepsilon$ presents inverse correlations with $E$ and $\mu$ in the surrounding carbonates but such correlations cannot be found in the Barnett Shale. In addition, the effect of $\varepsilon$ on $\nu$ is weak in all three formations.

**The prediction of S-wave velocity**

Pore aspect ratio $\alpha$ is not only a parameter for the evaluation of pore geometry in tight rocks, but also an important factor for the prediction of $V_s$. In the procedure for the inversion of $\alpha$, the criterion for the best match between measured and predicted $V_p$ not only gives an estimate of $\alpha$ but also a value of $V_s$ at the same time. Therefore, such a predicted value of $V_s$ can be regarded as an estimate of real $V_s$ under the effect of microstructures in rocks. Figure 8 (a) compares the real $V_s$ (black curve) measured in the borehole and $V_s$ (red curve) inverted using the method described above. Similarly, the same procedure can be conducted to predict $V_p$ from $V_s$, as shown in Figure 8 (b). Figure 8 (c) displays the inverted $\alpha$ from $V_p$ (blue curve) and $V_s$ (red curve), respectively.

**Conclusions**

We have built a rock physics model for shales based on the SCA method. The high frequency SCA method is suitable because low porosity and permeability prevent hydraulic connectivity and pore pressure equilibrium in shales.
Figure 7 Crossplots of crack density $\varepsilon$ versus geomechanical parameters Young’s Modulus $E$, Poisson’s ratio $v$, and shear modulus $\mu$ for the Marble Falls, Barnett and Ellenburger.

Figure 8 (a) predicting $V_s$ from $V_p$. (b) predicting $V_p$ from $V_s$. Black curves in (a) and (b) represent original well logs, and red ones predicted results. (c) Curves of aspect ratio inverted from $V_p$ (blue), and $V_s$ (red) for corresponding velocity predictions in (a) and (b).

We find that the values of aspect ratio in shale are stable with a mean value around 0.1, and the variation in pore aspect ratio in the Barnett Shale is much less than that in the surrounding Marble Falls and Ellenburger formations, which may imply the presence of more complex pore and crack systems in the surrounding carbonates. We also find that the crack density derived from porosity and aspect ratio has observable inverse correlations with Young’s modulus and shear modulus in the surrounding carbonates but such correlations are not obvious in the Barnett shale.

Finally, aspect ratio is not only a parameter for the evaluation of pore geometry, but can also be used as a constraint for the prediction of S-wave velocity from P-wave velocity, or vice versa. In this study, the prediction results indicate good agreements between predicted and real velocity for all three tight formations.

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References


