Rock Physics of Shales and Source Rocks

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First Question: What is Shale?

*Shale* -- a rock composed of mud-sized particles, such as silt and clay (Boggs, 2001). This most general classification is based on *particle size, not composition*.

Variations in usage:
- *Shale* is sometimes used to refer only to *fissile* rocks made of mud-sized particles, while
- *Mudstone* is sometimes used to refer to *non-fissile* rocks made of mud-sized particles, and
- *Siltstone* is sometimes used for rock with mud-sized particles, but low clay fractions.
What is Shale?

*Wentworth Scale of grain size*

\[ \phi = - \log_2 d \]

<table>
<thead>
<tr>
<th>Grain size (mm)</th>
<th>( \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>-5 vc</td>
</tr>
<tr>
<td>8</td>
<td>-4 c</td>
</tr>
<tr>
<td>4</td>
<td>-3 m</td>
</tr>
<tr>
<td>2</td>
<td>-2 f</td>
</tr>
<tr>
<td>1</td>
<td>-1 granule</td>
</tr>
<tr>
<td>0.50</td>
<td>0 vc</td>
</tr>
<tr>
<td>0.25</td>
<td>1 c</td>
</tr>
<tr>
<td>0.125</td>
<td>2 m</td>
</tr>
<tr>
<td>0.063</td>
<td>3 f</td>
</tr>
<tr>
<td>0.031</td>
<td>4 vf</td>
</tr>
<tr>
<td>0.015</td>
<td>5 c</td>
</tr>
<tr>
<td>0.008</td>
<td>6 m</td>
</tr>
<tr>
<td>0.004</td>
<td>7 f</td>
</tr>
<tr>
<td></td>
<td>8 vf</td>
</tr>
<tr>
<td></td>
<td>3 clay</td>
</tr>
</tbody>
</table>

*Mud*  
\( (d < 30 \mu m) \)
Shale Permeability
Permeability: Kozeny-Carman Relation

Kozeny-Carman model for permeability in a porous rock:

\[ K = \frac{B\phi^3 d^2}{\tau} \]

where:
- \( \phi \) porosity
- \( \tau \) tortuosity
- \( d \) typical grain diameter
- \( B \) geometric factor

Strong dependence on grain size
Small particle size leads to very small permeability

\[ \kappa = \frac{B \phi^3 d^2}{\tau} \]

Issue: What is shale permeability?

How does gas move through shale?

• As a gas phase through connected pores?

• Does it diffuse molecule-by molecule?

• Role of maceral porosity/permeability?

• Role of silty layers?
Fractures/
Brittleness
Brittleness increases the chances of naturally occurring fractures, as well as success of hydrofracs. Brittle materials accommodate strain (deformation) by breaking. In constrast ductile materials accommodate strain by “flowing.” Not only are ductile materials less likely to create permeable fractures, ductile materials will also allow man-made fractures to close or “heal.”

Important practical issue is how to determine geomechanical properties from geophysical measurements.
Brittleness is a complex function of lithology, composition, TOC, effective stress, temperature, diagenesis, thermal maturity, porosity, …
Quantifying Brittleness

Because material failure is important in many technologies, there are many attempts to define or quantify a Brittleness Index, e.g.

\[ B_1 = \frac{\sigma_c}{\sigma_t} \quad B_2 = \frac{\sigma_c - \sigma_t}{\sigma_c + \sigma_t} \quad B_2 = q\sigma_c \]

where
\[ \sigma_c = \text{Uniaxial compressive strength} \]
\[ \sigma_t = \text{Tensile strength} \]
\[ q = \text{Amount of fines in impact test} \]

Kahraman, 2003, Engineering Geology
Quantifying Brittleness

In terms of overconsolidation ratio

\[ OCR = \frac{\sigma_{V_{\text{max}}}}{\sigma_V} \]

\( \sigma_V \)  Vertical stress
\( \sigma_{V_{\text{max}}} \)  Vertical stress at max burial

(only valid for layered rocks and max principal stress is vertical)

Brittleness:

\[ B = \frac{\left(\sigma_c\right)_{OC}}{\left(\sigma_c\right)_{NC}} = OCR^b \]

Nygard et al., 2006, Marine and Petroleum Geology
Brittleness: Composition

Composition: There is anecdotal evidence that (1) silica (siltiness) and (2) calcite content increase brittleness. One index that is sometimes quoted:

\[ B(\%) = \frac{Q}{Q + Carbon + Clay} \]

An intuitive extension to calcite:

\[ B(\%) = \frac{Q + Calcite}{Q + Calcite + Carbon + Clay} \]
Brittleness: Composition

Issue: How to measure brittleness from logs? Calcite and quartz each have distinctly different Vp/Vs than shale. However when added, they might cancel changes in Vp/Vs.

\[
\left( \frac{V_P}{V_S} \right)_{\text{sand}} \leq \left( \frac{V_P}{V_S} \right)_{\text{shale}} \leq \left( \frac{V_P}{V_S} \right)_{\text{limestone}}
\]
Seismic Velocities
Impedance-Porosity Trends

Jack Dvorkin
Shale Anisotropy
Virtually any rock that has a visual layering or fabric at a scale finer than the seismic wavelength will be elastically and seismically anisotropic. Sources can include elongated and aligned grains and pores, cracks, and fine scale layering. Velocities are usually faster for propagation along the layering.
Seismic Anisotropy Due to Rock Fabric

Anisotropic velocities vs. pressure. (a) and (b) Jones (1983), (c) Tosaya (1982).
Velocity Anisotropy Resulting From Thinly Layered Kerogen

P-wave anisotropy in shales (from Vernik, 1990):

Vernik found that kerogen-bearing shales can have very large anisotropy, easily 50%.
P- and S-wave phase velocities depend on their direction of propagation and polarization. Hence, sonics measured on deviated wells do not measure the vertical velocities, as we often assume. Shear logs can be especially challenging if not oriented.
Organic-Rich Shales

Courtesy of Tiziana Vanorio

Stanford Rock Physics Laboratory
An Intrinsically Heterogeneous and Complex Rock

Mixture of **inorganic** and **organic** matter. The inorganic is clay, silt, carbonate, pyrite, etc. The organic (kerogen) appears as nano-particles (macerals) and hydrocarbons.

In some cases organics appear as inclusions in the inorganic background, and other times, the inverse.
What parameters are we interested in?

1) Quantity; 2) Quality; 3) Maturity

Pay
Type

Maceral
Composition

Hydrogen Index (HI)

Van Krevelen
Diagram

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Pressure-Velocity Sensitivity and Anisotropy vs. Maturity

Vernik et al., 1992
Vanorio et al., 2008

Table 2. Anisotropic elastic constants and parameters of a mature kerogen-rich shale calculated from measurements and derived for the microcrack-free shale.

<table>
<thead>
<tr>
<th>Conf. Pressure, MPa</th>
<th>C_{11}</th>
<th>C_{33}</th>
<th>C_{44}</th>
<th>C_{66}</th>
<th>C_{13}</th>
<th>ε</th>
<th>δ</th>
<th>δ’</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>53.2</td>
<td>23.2</td>
<td>11.0</td>
<td>19.0</td>
<td>8.4</td>
<td>0.65</td>
<td>0.27</td>
<td>0.32</td>
</tr>
<tr>
<td>70</td>
<td>56.2</td>
<td>36.7</td>
<td>14.4</td>
<td>19.3</td>
<td>13.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 (crack-free)</td>
<td>53.2</td>
<td>32.3</td>
<td>13.2</td>
<td>19.0</td>
<td>10.4</td>
<td>0.32</td>
<td>0.22</td>
<td>0.16</td>
</tr>
</tbody>
</table>

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Direction Perpendicular to the Plane Bedding

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Summary

• Shale is defined by particle size.
• Shale can have a very large range of compositions.
• Shale can have a large range of P- and S-wave velocities
  – Composition
  – Porosity
  – Effective stress
  – Compaction
• Shale Vp/Vs depends on composition, especially relative amounts of clay, silt, organics, and carbonate
• Shale can have a large range of anisotropies
  – Small if bioturbated
  – Large if a pronounced fabric
  – Silt and cementation can reduce anisotropy
• In kerogen-rich shales, properties depend on composition, TOC, and maturity.

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Issues

• Shale lab data are sparse, compared with sandstone and carbonate.
• Logs are also more common in reservoirs than shales.
• Other than models like soft-sediment and Raymer, we don’t have any comprehensive shale models.
• Shale anisotropy depends on many factors and is difficult to predict.
• Organic shales (oil shale and gas shale) can have a range of properties, depending on composition, TOC, maturity.
• For gas and oil shales, it is not clear what the geophysical questions are:
  – TOC?
  – Maturity?
  – Geomechanical?