Module for:
Introduction to Shaly Sand Analysis

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Shaly Formations: General Information

● The Archie equations for porosity and water saturation assume a clean formation with a non-conductive matrix.
● Shales conduct electricity — and shaly sand conductivity varies with clay type, shale origin, and fluid composition.
Shaly Formations: Issues

Shaly Formations:
- Fresh formation waters can cause conventional well log analysis to overestimate water saturation.
- Relatively saline (salty) formation waters lead to low resistivity, which may cause pay zones to be bypassed (or not recognized).
- Thinly-bedded zones may cause conventional well log analysis to underestimate porosity and to overestimate water saturation.
In formation evaluation, the terms "shale" and "clay" are used synonymously. In fact, shales may be:

- Mineralogically complex (many minerals).
- May have variable properties.

And for clay:

- May refer to a grain size (diameter < 0.004 mm).
- May refer to a class of minerals (e.g., illite, smectite, montmorillonite, chlorite, kaolinite).
Shaly Formations: Points of Interest

This lecture:

• Shales/clays have several origins and forms:
• Shales/clays affect the following:
  ■ Porosity.
  ■ Permeability.
  ■ $V_{Shale}$ (shale volume, as a fraction).
    — Estimates of $V_{Shale}$.
    — Assumptions regarding the reservoir.
    — Well log analysis.
What is *shale*:

- **Shale** is type of *clastic* sedimentary rock:
  - Comprised dominantly of clay minerals and other clay-size fragments.
  - Contains some silt-sized grains of:
    - Quartz.
    - Feldspar.
    - Other minerals.
    - May contain organic fragments. (source rock)
- Shale is fissile — splits along bedding planes.
- Claystone — massive features — not fissile.
What is *clay*:

- Clay is the name for a family of aluminosilicate minerals including:
  - Kaolinite ("discrete particle")
  - Chlorite ("pore lining")
  - Illite ("pore bridging")
  - Smectite
  - Montmorillonite

- Clay is a class of clastic sediments with a grain size (diameter) < 0.004 mm (< 4 microns)
  - May contain clay minerals, quartz, feldspar minerals, etc.

- Clays form *approximately* 40% of sedimentary rocks.
### Grain-Size Classification (Clastic Sediments)

<table>
<thead>
<tr>
<th>Name</th>
<th>Millimeters</th>
<th>Micrometers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boulder</td>
<td>4,096</td>
<td></td>
</tr>
<tr>
<td>Cobble</td>
<td>256</td>
<td></td>
</tr>
<tr>
<td>Pebble</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Granule</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Very Coarse Sand</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>0.5</td>
<td>500</td>
</tr>
<tr>
<td>Medium Sand</td>
<td>0.25</td>
<td>250</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>0.125</td>
<td>125</td>
</tr>
<tr>
<td>Very Fine Sand</td>
<td>0.062</td>
<td>62</td>
</tr>
<tr>
<td>Coarse Silt</td>
<td>0.031</td>
<td>31</td>
</tr>
<tr>
<td>Medium Silt</td>
<td>0.016</td>
<td>16</td>
</tr>
<tr>
<td>Fine Silt</td>
<td>0.008</td>
<td>8</td>
</tr>
<tr>
<td>Very Fine Silt</td>
<td>0.004</td>
<td>4</td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(modified from Blatt, 1982)
Sedimentary Rock Types:

Relative Abundances

- **Mudstone (Siltstone and shale) (clastic)**
  - ~75%
- **Sandstone and Conglomerate (clastic)**
  - ~11%
- **Limestone and Dolomite (carbonate)**
  - ~14%
### Detrital Mineral Composition: Shale/Sandstone

<table>
<thead>
<tr>
<th>Mineral Composition</th>
<th>Shale</th>
<th>Sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay Minerals</td>
<td>60 (%)</td>
<td>5 (%)</td>
</tr>
<tr>
<td>Quartz</td>
<td>30</td>
<td>65</td>
</tr>
<tr>
<td>Feldspar</td>
<td>4</td>
<td>10-15</td>
</tr>
<tr>
<td>Rock Fragments</td>
<td>&lt;5</td>
<td>15</td>
</tr>
<tr>
<td>Carbonate</td>
<td>3</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Organic Matter, Hematite, and Other Minerals</td>
<td>&lt;3</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

(modified from Blatt, 1982)
Sandstone: Major Components

- **Framework:**
  - Sand and silt-size detrital grains (load-bearing).

- **Matrix:**
  - Silt and clay-size detrital material.

- **Cement:**
  - Minerals precipitated post-deposition, during burial and diagenesis (several sequences possible).
  - Cements fill pores, may replace framework grains.

- **Pores:**
  - Voids among the above components.
Sandstone: Major Components (Schematic Diagram)

Geologist’s Classification

1. Framework
2. Matrix
3. Cement
4. Pores

Engineering "matrix"

Note different use of "matrix" by geologists and engineers

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Sandstone Composition: Framework Grains

Norphlet Sandstone, Offshore Alabama, USA
Grains ~0.25 mm in diameter/length

Photo by R. Kugler

Framework:
- KF = Potassium Feldspar (Stained yellow with a chemical dye)
- PRF = Plutonic Rock Fragment
- Q = Quartz
- P = Pore (Pores are impregnated with blue-dyed epoxy)
Comparison of Rock Composition:

Clastic Rocks

- Sand Grains
- Clay Matrix
- Chemical Cement

Average Sandstone

Average Mudrock (Shale)

Clay Matrix
- Illite
- Kaolinite
- Smectite

Chemical Cement
- Quartz
- Feldspar
- Rock Fragments

Carbonate Rocks

- Allochemical Grains
- Microcrystalline Matrix
- Chemical Cement

Average Sparry Limestone

Average Micritic Limestone

Fossils
- Pelloids
- Oolites
- Intractlasts

Calcite

Calcite

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PETROGRAPHIC SANDSTONE CLASSIFICATION

Petrographic Sandstone Classification

**QUARTZ + Chert**
- Quartzarenite

**Feldspathic Litharenite**
- Lithic Arkose
- Subarkose

**Sublitharenite**
- Subarkose

**Litharenite**
- Lithic Arkose

**Modified from McBride, 1963**
Origin of Shale and Clays: (Sandstone)

Detrital (particles)

Authigenic (Naturally Formed)
**Origin of Shale and Clays: (Sandstone)**

<table>
<thead>
<tr>
<th>Type</th>
<th>Dispersed Clay</th>
<th>Clay Lamination</th>
<th>Structural Clay (Rock Fragments, Rip-Up Clasts, Clay-Replaced Grains)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay Minerals</td>
<td>$\phi_e$</td>
<td>$\phi_e$</td>
<td>$\phi_e$</td>
</tr>
<tr>
<td>Detrital Quartz Grains</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detrital Quartz Grains</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Occurrence of Shale/Clay: Structural Shale

- **Structural Shale:**
  - Replaces matrix (or feldspar) or can occur as detrital grains.
  - May *not* affect porosity/permeability.
  - Example — clast lag in channel deposits.
  - Clay composition *may differ* from nearby shales.
Occurrence of Shale/Clay: Laminated Shale

- Laminated Shale:
  - Interlayered with sand.
  - Affects porosity/permeability.
  - Common scenario — shale laminae.
  - Composition should be similar to nearby shale.
Examples of Shale in Whole Core

- Whole Core Photograph, Misoa Sandstone, Venezuela, W. Ayers.
- From: *Simulator Parameter Assignment and the Problem of Scaling in Reservoir Engineering* — Halderson (1986).
Depositional Environment: River Deltas


STS084-721-029 Selenga River Delta, Lake Baykal, Russia May 1997

● Which environments are most likely to result in:
  ■ Structural shales/clays? (regular deposition)
  ■ Laminated shales/clays? (irregular deposition)
  ■ Clean sands? (high energy environment)
Bioturbation

- Regular Layers
- Irregular Layers
- Mottles (Distinct)
- Mottles (Indistinct)
- Homogeneous Deposits
- Bioturbated Sandstone (Whole Core)

Burrows
Occurrence of Shale/Clay: Dispersed Shale/Clay

- **Dispersed Shale/Clay:**
  - Pore-filling clays (very common).
  - Forms in-situ (authigenic clays form through diagenesis).
  - Composition may differ greatly from nearby shales.
  - Porosity and permeability reduction depend on volume and type of clay minerals.

![Dispersed Clay Diagram]

**Detrital Quartz Grains**

\[ \phi_e \]

**Clay Minerals**

"DISCRETE PARTICLE" KAOLINITE
Diagenesis

- **Diagenesis:**
  - Post-depositional chemical and mechanical changes that occur in sedimentary rocks.

- **Diagenetic effects:**
  - Compaction.
  - Precipitation of cement.
  - Dissolution of framework grains and cement.

- **Diagenesis may:**
  - Enhance or degrade reservoir quality.

- Whole Core Photograph, Miosa Sandstone, Venezuela, W. Ayers.
Sandstone Porosity: Intergranular Porosity

Porosity in sandstones is typically lower than that of an idealized packing of spheres due to:

- Variation in grain size.
- Variation in grain shape.
- Cementation.
- Mechanical and chemical compaction.

Scanning Electron Micrograph (photomicrograph by R.L. Kugler)
Norphlet Sandstone, Offshore Alabama, USA
Sandstone Porosity: Pore Throats with Overgrowths (1/2)

- Pores provide *volume* to store fluids.
  - Fluids can be stored between and/or within the grains.
- Pore throats connect pores — may constrict flow.
  - The "impedance" to flow imposed by the pore throat must be recognized.

Scanning Electron Micrograph (photomicrograph by R.L. Kugler)
Norphlet Sandstone, Offshore Alabama, USA

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Slide — 26
Sandstone Porosity: Pore Throats with Overgrowths (2/2)

Note the nature of the pore throat — and the associated overgrowths of clay.

Some overgrowths provide additional pore space known as microporosity.

Scanning Electron Micrograph (photomicrograph by R.L. Kugler)
Tordillo Sandstone, Neuquen Basin, Argentina
Dispersed Clay Types:

- **Kaolinite** — booklets, particles.
  - Moderate effect on permeability.
- **Chlorite** — linings, coatings.
  - Significant reduction in permeability.
  - Traps water.
- **Illite** — pore-bridging tangles.
  - Acts to choke pores and pore throats.
  - Significant reduction in permeability.
  - Illite will collapse when dry, yields erroneous estimates of porosity (too high).
Dispersed Clay Types: Authigenic Kaolinite

Authigenic Kaolinite

- Forms booklets or "discrete particles."
- Can cause significant reduction in permeability, generally moderate.
- Yields a high irreducible water saturation.
- Fines migration is also a possibility with Kaolinite.
- Kaolinite is NOT recognized using the conventional Gamma Ray (GR) log.

Secondary Electron Micrograph (Photograph by R.L. Kugler)
Carter Sandstone, North Blowhorn Creek Oil Unit
Black Warrior Basin, Alabama, USA
Dispersed Clay Types: Authigenic Chlorite

- Authigenic Chlorite
  - Forms a "pore lining" — i.e., a thin coat on the detrital grain surfaces.
  - Chlorite is rich in iron and will react with acids.
  - Generally occurs in deeply buried sandstone reservoirs.
  - Chlorite can significantly reduce permeability and tends to trap water.

Scanning Electron Micrograph (photomicrograph by R.L. Kugler)
Norphlet Sandstone, Offshore Alabama, USA

~ 10 µm
Dispersed Clay Types: Fibrous, Authigenic *Illite*

**Authigenic Illite**
- Illite is consists of "pore-bridging" filaments (or fibers) which can significantly reduce permeability.
- Illite generally does not have a significant impact on porosity.
- Can cause a high irreducible water saturation.
- Fines migration can be an issue with Illite.

Scanning Electron Micrograph (photomicrograph by R.L. Kugler)
Norphlet Sandstone, Hatters Pond Field, Alabama, USA
Intergranular Porosity And Microporosity

Porosity

- Intergranular pores contain hydrocarbons and water.
- Micropores (in clays) contain only water — technically this is an irreducible water volume.

Basic Porosity Types

Sandstone

Comment on Porosity/Permeability

- Table 2.11: Note that porosity is clearly a function of sorting.
- Table 2.16: Note that permeability is also a function of sorting.
- Technically, porosity is not a function of grain size, presuming that grain size is uniform.

**From:** SPE Monograph — Well Logging I, Jorden and Campbell (1984).

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**TABLE 2.11—POROSITY (FRACTION BULK VOLUME) OF ARTIFICIALLY MIXED AND WET-PACKED SAND**
(from Beard and Weyl™)

<table>
<thead>
<tr>
<th>Sorting</th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
<th>Very Fine</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper</td>
<td>Lower</td>
<td>Upper</td>
<td>Lower</td>
<td>Upper</td>
<td>Lower</td>
</tr>
<tr>
<td>Extremely well sorted</td>
<td>0.431</td>
<td>0.428</td>
<td>0.417</td>
<td>0.413</td>
<td>0.415</td>
<td>0.435</td>
</tr>
<tr>
<td>Very well sorted</td>
<td>0.408</td>
<td>0.415</td>
<td>0.402</td>
<td>0.398</td>
<td>0.408</td>
<td>0.412</td>
</tr>
<tr>
<td>Well sorted</td>
<td>0.380</td>
<td>0.384</td>
<td>0.381</td>
<td>0.388</td>
<td>0.391</td>
<td>0.397</td>
</tr>
<tr>
<td>Moderately sorted</td>
<td>0.324</td>
<td>0.333</td>
<td>0.342</td>
<td>0.349</td>
<td>0.339</td>
<td>0.343</td>
</tr>
<tr>
<td>Poorly sorted</td>
<td>0.271</td>
<td>0.298</td>
<td>0.315</td>
<td>0.313</td>
<td>0.304</td>
<td>0.310</td>
</tr>
<tr>
<td>Very poorly sorted</td>
<td>0.296</td>
<td>0.252</td>
<td>0.258</td>
<td>0.234</td>
<td>0.285</td>
<td>0.290</td>
</tr>
<tr>
<td>Average porosity</td>
<td>0.350</td>
<td>0.352</td>
<td>0.353</td>
<td>0.350</td>
<td>0.365</td>
<td>0.364</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.060</td>
<td>0.063</td>
<td>0.055</td>
<td>0.062</td>
<td>0.049</td>
<td>0.053</td>
</tr>
</tbody>
</table>

**TABLE 2.12—POROSITY AND PERMEABILITY OF HOLOCENE CARBONATE SEDIMENTS** (from Enos and Sawatsky™)

<table>
<thead>
<tr>
<th>Depositional Texture</th>
<th>Porosity (fraction bulk volume)</th>
<th>Permeability (darcies)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>Grainstone</td>
<td>0.445</td>
<td>0.40 to 0.53</td>
</tr>
<tr>
<td>Packstone</td>
<td>0.547</td>
<td>0.45 to 0.67</td>
</tr>
<tr>
<td>Wackestone</td>
<td>0.680</td>
<td>0.64 to 0.78</td>
</tr>
<tr>
<td>Very fine wackestone</td>
<td>0.705</td>
<td>0.67 to 0.73</td>
</tr>
<tr>
<td>Supratidal wackestone</td>
<td>0.635</td>
<td>0.61 to 0.66</td>
</tr>
</tbody>
</table>

**TABLE 2.16—PERMEABILITY (DARCIES) OF ARTIFICIALLY MIXED AND WET-PACKED SAND**
(from Beard and Weyl™)

<table>
<thead>
<tr>
<th>Sorting</th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
<th>Very Fine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper</td>
<td>Lower</td>
<td>Upper</td>
<td>Lower</td>
</tr>
<tr>
<td>Extremely well sorted</td>
<td>475</td>
<td>238</td>
<td>119</td>
<td>59</td>
</tr>
<tr>
<td>Well sorted</td>
<td>498</td>
<td>239</td>
<td>115</td>
<td>57</td>
</tr>
<tr>
<td>Moderately sorted</td>
<td>302</td>
<td>151</td>
<td>76</td>
<td>38</td>
</tr>
<tr>
<td>Poorly sorted</td>
<td>110</td>
<td>55</td>
<td>28</td>
<td>14</td>
</tr>
<tr>
<td>Very poorly sorted</td>
<td>45</td>
<td>23</td>
<td>12</td>
<td>6.0</td>
</tr>
</tbody>
</table>
Shaly Formations: Review

This lecture:

- Shales/clays have several origins and forms:
- Shales/clays affect the following:
  - Porosity.
  - Permeability.
  - $V_{Shale}$ (shale volume, as a fraction).
    - Estimates of $V_{Shale}$.
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    - Well log analysis.
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End of Presentation

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