A Multi-Measurement Core-Log Integration for Advanced Formation Evaluation of Oil Shale Formations: A Green River Case Study

S.L. Reeder, R. Kleinberg, M. Herron, M. Machlus, N. Seleznev, B. Vissapragada, Schlumberger

A. Burnham, American Shale Oil LLC

P. Allix, TOTAL SA
Key points

• Advanced logging measurements can provide estimations of:
  – Kerogen content of oil shales
  – Formation water salinity
  – Formation mineralogy
  – CO₂ emissions
Data

Logs

• Triple combo logs
  – Resistivity, porosity, lithology
• Elemental spectroscopy logs
  – Si, Ca, Ti, S, Fe, Mg, Al, K, Na, Cl
• Magnetic resonance
  – Porosity
• Dielectric dispersion
  – Porosity

Core

• 1500 ft of core
  – Slabbed and homogenized
• Fischer Assay
• Mineralogy
  – Dual Range FT-IR Spectroscopy
• Elemental analysis
  – XRF - oxides
  – ICPMS - trace elements
  – LECO - sulfur
  – Organic carbon
Porosity

\[ \Phi = \frac{V_{voids}}{V_{total}} = \frac{voids}{voids + solids} \]

Is kerogen part of the pore space?

Inorganic Minerals
- Mineral Model
  - Density: \( \rho \approx 2.64 \pm 0.05 \) g/cc

Kerogen
- Model Density: \( \Phi_{model} \)
  - MR
  - Dielectric

Water
- Density: \( \rho \approx 1.07 \) g/cc
- Density: \( \rho \approx 1.00 \) g/cc

TOM = Kerogen in Green River
Four methods of estimating Total Organic Matter (TOM):

- Petrophysical model
- Magnetic resonance
  - Porosity differences
- Dielectric dispersion
  - Porosity differences
- Elemental spectroscopy logs
  - TC from inelastic scattering
  - TIC from elemental spectroscopy

Compare to core:
- TC from combustion
- TIC from acid treatment
Estimating Formation Salinity

- Log estimations
  - Magnetic resonance and resistivity
  - Elemental spectroscopy logs
- Core Chlorine measurements
- Hydrological measurements
### Core Mineralogy

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Mahogany (R7)</th>
<th>Mahogany (R7) B-groove</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>R6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R5</td>
<td></td>
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<td>L4</td>
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<td>R4</td>
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<td>L2</td>
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<td>R1</td>
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<td>L0</td>
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</tr>
<tr>
<td></td>
<td>R0</td>
<td></td>
</tr>
</tbody>
</table>
Petrophysical Model

- Volumes ($V$)
  - Clay group
  - Quartz group
  - Carbonates
  - Feldspars
  - Kerogen
  - Buddingtonite
  - Dawsonite
  - Nahcolite
  - Pyrite
  - Water - bound and free
Petrophysical Model

- Inputs (Log)
  - Elemental spectroscopy logs
    - Si, Ca, Fe, Al, S, K, Na
  - Total carbon
  - Magnetic resonance
  - Photoelectric factor
  - Density
  - Neutron porosity

- Endpoints (C)
  - Response of log \( j \) for 100% of mineral \( i \)

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Petrophysical Model Matches Core Data

<table>
<thead>
<tr>
<th>Zone</th>
<th>Quartz group</th>
<th>Clay group</th>
<th>Feldspar group</th>
<th>Carbonate group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parachute Creek</td>
<td>quartz</td>
<td>illite, smectite, kaolinite, chlorite, glauconite, muscovite, biotite</td>
<td>sodium feldspar (albite), potassium feldspar (orthoclase), analcime</td>
<td>dolomite, calcite, high magnesium calcite, aragonite, ankerite, siderite</td>
</tr>
<tr>
<td>Garden Gulch</td>
<td>quartz, opal-A</td>
<td>different proportions of the above constituents</td>
<td>absent</td>
<td>dolomite, ankerite</td>
</tr>
</tbody>
</table>
Petrophysical Model Results

- Buddingtonite
- Clay
- Dolomite
- Feldspars
- Kerogen
- Quartz

Log Volume Fraction vs. Core Volume Fraction
- Apply model to second well
  - ~230 m away
CO$_2$ Production from Carbon Degradation

**Mineral** | **Carbon wt%**
--- | ---
Ankerite | 11.6%
Aragonite | 12.0%
Calcite | 12.0%
Dawsonite | 8.3%
Dolomite | 13%
Nahcolite | 14.3%
Siderite | 10.4%

Temperature

350°C

565 ft
Summary and Conclusions

• Green River Formation consists of complex mineralogy
• Advanced logs improve modeled mineralogy for this complex environment
  – Magnetic resonance, spectroscopy, dielectric
• Core measurements match log-estimations
  – Organic matter content
  – Formation salinity
• Modeled mineralogy can help in environmental planning
  – Maximum potential CO$_2$ production