Practical use of core data for shale petrophysics
A petrophysicists perspective

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Denver, Colorado
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Short Course 1: Laboratory measurements of shale gas cores
## What do we want from our cores?

<table>
<thead>
<tr>
<th>Property of interest</th>
<th>Core data</th>
<th>Most useful log data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>Crushed dry rock</td>
<td>Density (mostly)</td>
</tr>
<tr>
<td></td>
<td>He porosimetry</td>
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<tr>
<td>TOC</td>
<td>LECO or RockEval</td>
<td>GR, density, resistivity</td>
</tr>
<tr>
<td>Water saturation</td>
<td>As-received retort or Dean-Stark</td>
<td>Resistivity with kerogen corrected shale porosity</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>XRD, FTIR, XRF</td>
<td>Most + ECS-style logs</td>
</tr>
<tr>
<td>Permeability</td>
<td>Pulse decay on crushed rock</td>
<td>Tough..............</td>
</tr>
<tr>
<td>Geomechanics</td>
<td>Static moduli</td>
<td>DTC, DTS, RHOB, or their synthetic substitutes</td>
</tr>
<tr>
<td>Geochemistry</td>
<td>Ro, S1-S2-S3, etc.</td>
<td>varies</td>
</tr>
</tbody>
</table>
Approaches to shale log analysis

- Global/stochastic
  - Characterize end member properties
  - Invert the logs for properties that best fit the observed log character
  - ELAN, Multimin, etc.
  - Key question: how do I know, or guess at, the end member points?
    - What is the GR, RhoB, & HI of kerogen?
    - What is the inorganic grain density of the clay components?
Approaches to shale log analysis

- Global/deterministic
  - Characterize properties using broad collections of shale samples, either globally or basin/play specific
  - Schmoker equations
  - \( \Delta \text{LogR} \)
  - Schlumberger SpectroLith a common implementation
  - CoreLabs shale gas JIP’s are used via a data mining approach for many companies
Schmoker’s TOC eqn’s

TOC (v/v) = \( \left( \rho_{\text{gray sh}} - \rho_b \right) / 1.378 \)  
(1979 eqn)

TOC (v/v) = \( \left( \text{GR}_{\text{gray sh}} - \text{GR} \right) / (1.378 * A) \)  
(1981 eqn)
TOC from bulk density: specific play calibration

New Albany Shale, Illinois basin
EGSP cores (1976-1979), all blue logs
Basically a sonic F overlay

Globally determined eqn’s published by Passey et al.

\[ \Delta \log R = \log_{10} \left( \frac{R}{R_{bl}} \right) + 0.02 (\Delta T - \Delta T_{bl}) \]

\[ TOC = \Delta \log R \times 10^{(2.297 - 0.1688 \text{LOM})} \]

Most people worry about the LOM parameter, but just use the constants as published
deltaLogR

Passey et al, 2010, SPE 131350
TOC (wt %) = ΔlogR * 10^(2.297 - 0.1688*LOM)

Passey et al, 1990, AAPG 74 (12) 1777-1794
\[ \Delta \log R = \log_{10} \left( \frac{R}{R_{bl}} \right) + 0.02 (\Delta T - \Delta T_{bl}) \]

\[ \text{TOC} = \Delta \log R \times 10^{(2.002 - 0.1749 \text{LOM}), \text{ for LOM} = 9} \]
Deterministic suite of regression eqn's to compute mineral volumes and kerogen-free grain density

\[ \text{RhoM}_{\text{ecs}} = a + b \text{ Si} + c \text{ Ca} + d \text{ Fe} + e \text{ S} \]
Biggest risks......

- Regional or global equation does not apply locally & you don’t know that.
- Variable selected does not really correlate very well with property of interest.
  > e.g. gamma ray, because \( V_{uranium} \) is not a simple function of TOC.
- Co-linearities
  > e.g. using density to predict both porosity and TOC.
Approaches to shale log analysis

- **Local/deterministic**
  - Calibrate our log models in restricted areas, down to individual wells
  - Simple linear or non-linear regressions
    - GR vs. TOC, RHOB vs. TOC
  - Multiple linear regression
  - Multiple non-linear regression
    - includes neural networks
Local calibration to core
Practical issues

- Sample depths have to be accurate
- Core-log depth shifting has to be precise
- Need to work in consistent units
  - e.g. fractional bulk volume
- Need to extract log data to correlate with core values at the appropriate depths
  - Is it appropriate to average log data, when it is already sampling a much larger reservoir volume than the core data?
Not all critical variables are measured in the lab.

\[ \rho_b = \rho_g \phi_f (1 - S_{wT}) + \rho_w \phi_f S_{wT} + \rho_m (1 - \phi_f - TOC) + \rho_{TOC} \cdot TOC \]  

where:

- \( \rho_b \) = log-measured subsurface bulk density (g/cc)
- \( \rho_g \) = gas density (g/cc)
- \( S_{wT} \) = total water saturation (dec)
- \( \rho_w \) = connate water density (g/cc)
- \( \rho_m \) = grain density (g/cc)
- \( \rho_{TOC} \) = organic carbon density (g/cc)

When Equations 12 and 13 are combined with Equation 10 and inverted for porosity (\( \phi_T \)), the result is:

\[ \phi_T = \frac{\rho_m - \rho_b \left( \frac{w_{TOC}}{\rho_{TOC}} - w_{TOC} + 1 \right)}{\rho_m - \rho_b + w_{TOC} \rho_b \left( 1 - \frac{\rho_m}{\rho_{TOC}} \right)} \]

- But, we don’t measure the inorganic (kerogen free) grain density, nor the kerogen density. We have to solve for them somehow.
What do we do?

- Merge and convert core data into one spreadsheet
  - Shale rock properties, GRI method, TRA, etc.
  - Geochem data (TOC, S1, Tmax, etc.)
  - XRD data, preferably as bulk rock v/v accounting for $V_{kerogen}$ and porosity
  - Canister gas contents
  - Adsorption isotherm data (reduced)
  - Anything else clearly relevant to the log model
Get the data into a pile.....

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</table>

- C1: LOGDEPTH
- C2: CDEPTH
- C3: COREG
- C4: COREPTA
- C5: COREMC
- C6: COREFUR
- C7: COREGR
- C8: CCRUS
- C9: CLOSS
- C10: CMIC
- C11: M.getTotal
- C12: CPHI
- C13: GF
- C14: CORES
- C15: CROK
- C16: CRHO
- C17: CSG
- C18: CSO
- C19: CSW

The table contains various core data columns, including core gamma scan and core desorption data, along with other related measurements and calculations.
Core-log depth shift

- Merge in the core gamma scan
- Depth shift, honor the physical breaks
- Don’t interpolate
- Convert core depths to log depth, then import
- Keep an audit trail!
  - \( L = C + x \)
Export the log data

- Once we know where the core data belongs, we export the log curve data at every sample depth for analysis in a statistical package
- Merge the core and log data sets
- The more data you have at the same depths, the better........
Let the stats package do the heavy lifting

\[ XRD_{\text{CLAY}} = -60.48 - 44.90 \times \text{PHIDN} + 0.1973 \times \text{DTC} + 2.655 \times \text{ct\_root} \]
### Multiple linear regression from a list of possible variables

Summary of the variables selection:

<table>
<thead>
<tr>
<th>No. of variables</th>
<th>Variables</th>
<th>MSE</th>
<th>R²</th>
<th>Adjusted R²</th>
<th>Mallows' Cp</th>
<th>Akaike's AIC</th>
<th>Schwarz's SBC</th>
<th>Amemiya's PC</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>ct_root</td>
<td>25.062</td>
<td>0.687</td>
<td>0.620</td>
<td>8.135</td>
<td>127.579</td>
<td>130.906</td>
<td>0.329</td>
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<tr>
<td>2</td>
<td>DTC / ct_root</td>
<td>20.847</td>
<td>0.747</td>
<td>0.691</td>
<td>1.911</td>
<td>121.330</td>
<td>126.321</td>
<td>0.280</td>
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<tr>
<td>3</td>
<td>PHIDN / DTC / ct_root</td>
<td><strong>18.829</strong></td>
<td><strong>0.778</strong></td>
<td><strong>0.727</strong></td>
<td><strong>-0.344</strong></td>
<td><strong>118.261</strong></td>
<td><strong>124.915</strong></td>
<td><strong>0.258</strong></td>
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<tr>
<td>4</td>
<td>PHIDN / DTC / DTS / ct_root</td>
<td>19.219</td>
<td>0.780</td>
<td>0.728</td>
<td>1.396</td>
<td>119.928</td>
<td>128.246</td>
<td>0.269</td>
</tr>
</tbody>
</table>

*The best model for the selected selection criterion is displayed in blue*
Kill the outlier
- Solve for all the critical variables
  - RhoMa inorganic
  - Rho organic matter (kerogen)
  - Porosity & fluid saturations
  - Mineral volumes
  - Permeability, if you are brave……
  - Gas contents
- Deterministic approach, with local calibration to the core
Gas content

- Free gas falls out of the porosity - Sw computations
  - Need to know FVF
  - Need to correct for volume occupied by adsorbed gas (SPE 131772)
  - Reality check against canister off-gas data

- Adsorbed gas falls out of a Langmuir model
  - We solve for VL as \( f(\text{TOC}) \)
  - \( PL \) also comes from Solver instead of average
  - Observed \( Gc \) at \( P \) is the ground truth
  - We never, ever, have enough isotherm data
  - We also ignore temperature as a variable
Log data are far more abundant than core, and sample a greater volume of the reservoir out there, so accurate log models are essential for our evaluations of plays, areas, and wells.

We use cores to calibrate our models to the rock (no duh...).

If the core data are inaccurate, or the meaning of the measurement is unclear, our models will be useless and misleading.