Petroleum Systems in the Permian Basin: Targeting optimum oil production

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Outline

• Introduction
• Background
• Petroleum Systems
  – Classification
  – Organofacies
• Sample quality
• Identifying best oil zones
• Oil SARA assessment
• Thermal maturity assessments
• Restoring oil and predicting quality/phase
• Alpine High
• Synopsis
Performance Improvement

Permian Region
New-well oil production per rig

Source: EIA 2017

Drilled but Uncompleted
Permian Basin

Jan-17
Jan-16

Drilled-but-Uncompleted (DUC) Wells

Source: TCU Energy Institute
“EOG Resources: Identifying Best Horizontal Targets”

Where might such complexities occur in petroleum system(s)?

Understanding controls on target(s) becomes a key component in achieving the best production results.
Prediction of Petroleum Type (phase) vs maturity parameters

Modified from SPE Monograph 20

<table>
<thead>
<tr>
<th>Product</th>
<th>Methane [C₁] (mole %)</th>
<th>Heptane Plus (C₇ in mole %)</th>
<th>GOR (acf/stb)</th>
<th>Yield (bbl/mmcf)</th>
<th>Oil Gravity (°API)</th>
<th>Color of Liquid</th>
<th>Approximate %Rφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Oil</td>
<td>&lt; 70</td>
<td>&lt; 56</td>
<td>100 - 2,000</td>
<td>na</td>
<td>20 - 39</td>
<td>Green to Black</td>
<td>&lt; 0.95</td>
</tr>
<tr>
<td>Volatile Oil</td>
<td>70 - 80</td>
<td>&lt; 22</td>
<td>1,000 - 3,499</td>
<td>na</td>
<td>40 - 49</td>
<td>Light to Dark Amber</td>
<td>0.95 - 1.15</td>
</tr>
<tr>
<td>Gas Condensate</td>
<td>80 - 84</td>
<td>&lt; 8</td>
<td>3,500 - 4,999</td>
<td>200 - 285</td>
<td>50 - 54</td>
<td>Light Amber</td>
<td>1.15 - 1.25</td>
</tr>
<tr>
<td>Rich Wet Gas</td>
<td>84 - 88</td>
<td>&lt; 4</td>
<td>5,000 - 19,999</td>
<td>50 - 200</td>
<td>55 - 60</td>
<td>Translucent</td>
<td>1.25 - 1.35</td>
</tr>
<tr>
<td>Lean Wet Gas</td>
<td>88 - 92</td>
<td>&lt; 0.82</td>
<td>20,000 - 99,999</td>
<td>10 - 50</td>
<td>&gt; 60</td>
<td>Clear</td>
<td>1.35 - 1.50</td>
</tr>
<tr>
<td>Dry Gas</td>
<td>&gt; 92</td>
<td>na</td>
<td>&gt; 100,000</td>
<td>na</td>
<td>na</td>
<td>&gt; 1.5</td>
<td></td>
</tr>
</tbody>
</table>

Refs: Baker et al., 2015; Whitson, 2017; Whitson and Breule, 2000

Permian Basin Plays

Source: 7s Oil and Gas
Stratigraphy with oil and rock samples analyzed

Permian Basin Petroleum Systems

- Permian Guadalupian (3)
- Permian Leonardian Bone Springs (2)
- Permian Spraberry
- Permian Wolfcampian (2)
- Pennsylvanian (3)
- Mississippian Barnett Shale
- Devonian-Mississippian Woodford Shale (2)
- Ordovician Simpson Formation (2)

Refs: Jones and Smith, 1965; Williams, 1977; Jarvie et al., 2001; Hill et al., 2003; Curtis and Zumberge, 2017
Why is it more difficult to produce black oil from tight shale?

- Permeability
- Molecular size: physical limitation
- Viscosity: resistance to flow
- Polarity:
  - adsorptive affinity
  - Wettability
- GOR: pressure
- et al. ...

Select Risk Factors for plays and targets

<table>
<thead>
<tr>
<th>Unconventional Development Risk Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF-1 Oil Crossover</td>
</tr>
<tr>
<td>RF-2 TOC_{original}</td>
</tr>
<tr>
<td>RF-3 H_{original}</td>
</tr>
<tr>
<td>RF-4 TOC_{present-day}</td>
</tr>
<tr>
<td>RF-5 H_{present-day}</td>
</tr>
<tr>
<td>RF-6 Depositional System</td>
</tr>
<tr>
<td>RF-7 Source or Hybrid</td>
</tr>
<tr>
<td>RF-8 Maturity</td>
</tr>
<tr>
<td>RF-9 TR</td>
</tr>
<tr>
<td>RF-10 SARA</td>
</tr>
<tr>
<td>RF-11 API gravity</td>
</tr>
<tr>
<td>RF-12 GOR</td>
</tr>
<tr>
<td>RF-13 Porosity</td>
</tr>
<tr>
<td>RF-14 Permeability</td>
</tr>
<tr>
<td>RF-15 Oil saturation</td>
</tr>
</tbody>
</table>

in presentation
discussed in talk
Oil Content in Rock Sample as measured by thermal extraction

Total Oil = (S1 \text{WR} - S1 \text{extracted rock}) + (S2 \text{whole rock} - S2 \text{extracted rock}) + E.L.

Evaporative Losses = S1 \times (\text{GC Fingerprint produced oil} / \text{GC Fingerprint of extracted oil})

- The more organic-rich reservoir, E.L. is lower (depending on handling)
- The more organic-lean reservoir, E.L. is higher

Wolfcamp Oil Crossover

Data from Jarvie et al. (2001)

High TOC and even high oil contents are not necessarily indicative of producible oil. Excess oil relative to TOC is necessary to exceed sorptive capacity of kerogen, bitumen and rock matrix.
Best Interval to Produce: highest TOC?

Forward and Reverse Basic Model

Restored Oil (S1)

Total oil (measured plus restored) allows gross estimate of OOIP

Geochemical Estimated Oil-in-Place

If they do not agree... difference is expelled oil

Kerogen Conversion oil

Usually higher than restored oil; indicative of expulsion
Restored (original) Petroleum Potential:
Wolfcamp

Slope of these restored values is indicative of original hydrogen index, i.e., 521 and 652 mg oil potential/g TOC for Delaware and Midland basins, respectively.

Wolfcamp Generation Potential:
Midland vs Delaware Basin

Midland Wolfcamp at 60% TR and Delaware Wolfcamp at 80% TR (on average)
Comparison of Archived vs Fresh Cuttings

Samples from an offset well and compared to the archived cuttings from the original well
(Data courtesy of Gunn Oil Corp.)

Archived cuttings are hypothesized to be oxidized which lowers the pyrolysis effluent concentration yielding lower values of TOC and S2 due to increased CO$_2$ in effluent.

Ref: Jarvie, 2017

Impact of Sample Quality

While the Humble cuttings data shows variation from the fresh analysis of Barnett Shale, the Humble core data agrees. Cores were also archived but appear to be relatively unaffected by a decade of storage.

Thermal Maturity Techniques

Techniques for Evaluation of Thermal Maturity

<table>
<thead>
<tr>
<th>Method</th>
<th>Industry Standard</th>
<th>Variability</th>
<th>Range</th>
<th>Price</th>
<th>Delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitrinite reflectance</td>
<td>X</td>
<td>High</td>
<td>complete</td>
<td>Mod</td>
<td>Slow</td>
</tr>
<tr>
<td>Kerogen color</td>
<td>Mod</td>
<td>oil zone</td>
<td>Mod</td>
<td>Slow</td>
<td></td>
</tr>
<tr>
<td>Rock-Eval Tmax</td>
<td>X</td>
<td>High</td>
<td>oil zone</td>
<td>Low</td>
<td>Fast</td>
</tr>
<tr>
<td>Kerogen conversion ratio</td>
<td>Low</td>
<td>complete</td>
<td>Low</td>
<td>Fast</td>
<td></td>
</tr>
<tr>
<td>Dry gas ratio</td>
<td>Low</td>
<td>complete</td>
<td>Low</td>
<td>Fast</td>
<td></td>
</tr>
<tr>
<td>Carbon isotopes</td>
<td>X</td>
<td>Low</td>
<td>complete</td>
<td>High</td>
<td>Mod</td>
</tr>
<tr>
<td>Pyrolysis GC MS</td>
<td></td>
<td>oil zone</td>
<td>High</td>
<td>Mod</td>
<td></td>
</tr>
<tr>
<td>Biomarkers (standard approach)</td>
<td>Mod</td>
<td>oil zone</td>
<td>High</td>
<td>Slow</td>
<td></td>
</tr>
<tr>
<td>Aromatic hydrocarbons</td>
<td></td>
<td></td>
<td>complete</td>
<td>High</td>
<td>Fast</td>
</tr>
<tr>
<td>GC fingerprinting</td>
<td>Mod</td>
<td>complete</td>
<td>High</td>
<td>Fast</td>
<td></td>
</tr>
</tbody>
</table>

Discussed in presentation

Thermal Maturity Assessments: which is correct?

The most difficult task for an organic petrologist is to find indigenous woody plant debris, i.e., vitrinite particles, in a deep marine setting where most unconventional shales were deposited and preserved.

Maturity is a risking process and requires accurate and reproducible data for correlation to production.
Reflectivity increases due to increasing aromaticity

HIGH VOLATILE COAL (35% VOL. M)  MEDIUM VOLATILE BIT. COAL (22% VOL. M)  ANTHRACITE (5% VOL. M)

Stability varies by structural configurations

Control:  kinetic  thermodynamic  kinetic
Melting point:  -25°C  -48°C  13°C

1,2-dimethylbenzene  1,3-dimethylbenzene  1,4-dimethylbenzene
(ortho-xylene)  (meta-xylene)  (para-xylene)

Taylor et al., 1998

Comparison of Bitumen Reflectivity Equations at the critical volatile oil window (0.95 to 1.15%Roe), there can be considerable variation in predicted Roe equivalents.

\[ y = 1.4531x - 0.1512 \]

1:1 Line

0.30%Ro difference
For the most reliable Tmax data, organic-rich (bitumen-rich) shales must be solvent extracted prior to analysis.

Comparison of unextracted and extracted samples of Upper Bakken Shale. Tmax values of solvent-extracted rock average 5°C higher. The average Tmax value for whole rocks is 432°C versus 437°C Tmax for solvent-extracted rock or a calculated equivalent %Ro(Tmax) of 0.62% versus 0.71% (using the 2001 equation). This is the difference between immature and early mature Bakken Shale. Modified from Jarvie et al. (2011).

This is indicative of how strongly petroleum is sorbed into the kerogen and rock matrix.
Tmax to %Ro Correlation Data

2001: %Roe(Tmax) = 0.0180 x Tmax – 7.16
2018: %Roe(Tmax) = 0.0165 x Tmax – 6.51

<table>
<thead>
<tr>
<th>Tmax (°C)</th>
<th>2001 Equation</th>
<th>2018 Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>430</td>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>435</td>
<td>0.67</td>
<td>0.66</td>
</tr>
<tr>
<td>440</td>
<td>0.76</td>
<td>0.75</td>
</tr>
<tr>
<td>445</td>
<td>0.85</td>
<td>0.83</td>
</tr>
<tr>
<td>450</td>
<td>0.94</td>
<td>0.91</td>
</tr>
<tr>
<td>455</td>
<td>1.03</td>
<td>0.99</td>
</tr>
<tr>
<td>460</td>
<td>1.12</td>
<td>1.08</td>
</tr>
<tr>
<td>465</td>
<td>1.21</td>
<td>1.16</td>
</tr>
<tr>
<td>470</td>
<td>1.30</td>
<td>1.24</td>
</tr>
<tr>
<td>475</td>
<td>1.39</td>
<td>1.32</td>
</tr>
<tr>
<td>480</td>
<td>1.48</td>
<td>1.41</td>
</tr>
</tbody>
</table>

Most reliable results for Tmax derived from solvent-extracted rock samples. Preferred solvent for best clean-up of sample is a binary azeotrope of chloroform-methanol.

Full article posted at:


High Maturity Isotopic Reversal:
ethane becomes lighter below ca. 5% gas wetness (ca. 1.5%Ro)

Data from Zumberge et al. (2012)
Be Careful with Isotopic Maturity Graphics

Check ethane reversal before utilizing a similar graphic.

Ethane reversal results in lower predicted thermal maturity values.

Data from Zumbeke et al. (2012)

Correlation of Quantitative Aromatic Hydrocarbons to Thermal Maturity

Recall the aromaticity increase with maturation. This is reflected in ratios of varying stability aromatic hydrocarbons (Hill et al. 2004)

These are ratios of various aromatic hydrocarbons.

Ratios from Hill et al., 2004
Aromatic Hydrocarbon-derived thermal maturity (%Roe(ARO1))

Quantitative aromatic hydrocarbons work on either oils or rock extracts. They are also highly reproducible independent of any operator induced decisions other than correct identification and integration of peaks.

Ref: Don Rocher, 2015, Geomark Research

Secondary Oil (bitumen) Cracking

- Cracking of any product formed from kerogen cracking, i.e., second products
  - Oil cracking = secondary cracking
  - Oil is comprised of:
    - Saturates
    - Aromatics
    - Resins
    - Asphaltenes

Secondary oil cracking is not just saturate fraction cracking so often cited in presentations and papers. The entirety of petroleum cracks yielding lighter oil and more gas through the entire generation windows for oil and gas. This is proven by increasing oil quality (API gravity) and GOR with maturation.
Petroleum Products Generated from Kerogen Decomposition

SARA Fractions
have dramatically different properties even though all are part of petroleum

- Hydrocarbons
  - Saturates
  - Aromatics

  **Properties**
  - Non-polar
  - Largely non-adsorptive
  - Not usually viscous except when high molecular weight (>C40) waxes present
  - Used for biomarker and aromatic analysis

- Non-hydrocarbons
  - Resins
  - Asphaltenes

  **Properties**
  - Polar
  - Highly adsorptive
  - Highly viscous
  - Can be used as analogs for kerogen
Petroleum (Bitumen) and Secondary Cracking as shown in Lewan and Pawlewicz (2017)

Petroleum (Bitumen) and Secondary Cracking in reality: it is a continuous process throughout the oil and gas windows

Refs: Behar et al., 2008; Pepper and Corvi, 1995; Lewan and Pawlewicz, 2017
On the way to the volatile oil window

Prediction of GOR Break:
volatile oil to gas condensate occurs at about 1.15%Ro or 3500 scf/stb

Constant heating rate model: 2.3°C/Ma from 15°C to 200°C
Petroleum Systems
Retention, Expulsion, Migration, and Fractionation

Fractionation occurs on all petroleum movement whether natural or induced

Wettability / Cracking
of resins and asphaltenes
Such bonding includes within organic matter both kerogen and petroleum but also water wet inorganic matrices

Hydrogen Bonding enhanced in:
- -OH
- -SH

Such bonding allows resins to weakly bond to water.
Mobility and Expulsion Fractionation

Mobility results in higher amounts of saturates and aromatics in expulsion.

Post-Expulsion fractionation of Petroleum in source rock.

Comparison of Shale Reservoir Rock to Produced (dead) Oil

Source Rock Extract Fractions

Oil Fractional Fractions
**SARA: GOOD vs POOR**

**TCU Energy Institute**

**Wolfcamp Shale:**

Impact of thermal maturity (primary and secondary cracking) on SARA composition
Production Fractionation:
what reaches the surface is not necessarily what is in the reservoir itself
In such cases such a differentiation indicates producibility issues.

Factors Affecting S1:
lithofacies

Stored for exactly the same amount of time and conditions, the shale member retains far more hydrocarbons than the Middle Member

This loss is evaporative loss (EL)
which can be restored for volatile oils and condensates as shown on the following slides.

Jarvie et al., 2011
Light and C_{15}^- Hydrocarbons are lost from dead oil or oils extracted from source or reservoir rocks for volatile oils, condensates.

Peaks in red are less evaporated and form an exponential trend by alkane number.
An exponential fit to the less evaporated sample provides an exponential factor that is indicative of thermal maturity; the pre-exponential factor is a function of concentration.

Plotting molar yields on a logarithmic scale shows the slope of an oil very clearly. With increasing maturity the slope (left to right causeway) increases dramatically.

See also Holba et al., 2014.
Once the best fit equation is established the entirety of the petroleum composition may be projected C\textsubscript{1} to C\textsubscript{40} (applicable to volatile oils and condensates only).

Exponential Restoration of C\textsubscript{1} through C\textsubscript{40}
Predicted in situ Gas to Oil Index: 63%

Restored Values C\textsubscript{1} to n-C\textsubscript{40} and Gas-to-Oil Index for Bakken Middle Member extract relative to produced oil.
Eagle Ford: Calculated vs Produced Oil GORs

\[ y = 0.9611x + 782.6 \]
\[ R^2 = 0.9351 \]

Gechem Predicted vs Reported GOR
Permian Basin

\[ R^2 = 0.9394 \]
**Gas-to-Oil Ratio through time (Wolfcamp example)**

- **30 day**
  - Production: 1,283 scf/stb
  - Intrinsic GOR: 1,412 scf/stb

- **60 day**
  - Production: 2,146 scf/stb
  - Intrinsic GOR: 3,219 scf/stb

- **90 day**
  - Production: 3,219 scf/stb
  - Intrinsic GOR: 3,219 scf/stb

**Intraformational Variability of GOR**

- **Zone 1**
  - Average: 2898 scf/stb

- **Zone 2**
  - Average: 3111 scf/stb

**Gas-to-Oil Ratio (GOR in scf/stb)**
High Diamondoid Content in Oil Window Maturity Oils
indicative of secondary, high maturity oil charge

Migrated, high maturity oil charge in low maturity oils

Alpine High
Fasken 34-1, Reeves County, Texas

- Apache Mont Blanc 3H: 22,441 24-hr IP GOR
- Apache Cheyenne 1H: 28,709 24-hr IP GOR
- Apache Weissmies 1H: 25,345 24-hr IP GOR
- Apache Spanish Trail 1H: 60,037 24-hr IP GOR

Alpine High Barnett and Woodford (3) Wells

- Christmann, 2016 (Apache Barclays presentation)
Analysis of GC Histograms from Alpine High: exponential fit of GC histograms

Assessment of Oil Type/Phase:
Wolfcamp from central Reeves County, Texas and Alpine High Barnett and Woodford
Synopsis

- Sample Quality may affect results/interpretation
- SARA (saturates, aromatics, resins, and asphaltenes (non-polars vs polars) play an important role in mobility and fractionation
- Quantitative aromatic hydrocarbons is perhaps the best thermal maturity technique
  - Oils and Rock extracts
- Restored oil and GOR may be predicted from GC analysis of oils and rock extracts
- Alpine High Barnett and Woodford GORs are predicted from restored GC data

Thank you.

Comments or Questions?
References


Behar, F., F. Lorant, and M. Lewan, 2008, Role of NSO compounds during primary cracking of a Type II kerogen and a Type III lignite, OG, 39, p. 1-22


Jacob, H., 1989, Classification, structure, genesis, and practical importance of natural solid oil bitumen (“migrabitumen”), Int. Coal Geol., 11, 65-79.


