Petroleum System Charge Analysis for Liquid-Rich Unconventional Plays*

Michael Abrams ¹

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Abstract

Liquid-rich unconventional (LRU) plays have become a significant worldwide exploration target. We have seen greater emphasizes on defining the key petroleum systems factors required for a viable LRU play given the current lower price environment. Unlike the conventional system which requires off structure generation and migration, the liquid-rich unconventional petroleum system requires little or no migration. The liquid-rich unconventional acts as both source and reservoir; or the source rock is juxtaposed against or inter-bedded within the reservoir requiring minimal migration. There are many similarities to the conventional petroleum system but key fundamental differences are critical in understanding liquid-rich unconventional play potential. One must keep in mind not all organic rich oil generating source rocks will provide an economic liquid-rich unconventional petroleum system. Key petroleum system factors must be in place for an economic liquid-rich unconventional petroleum play to work (amount and type of organic matter type; source rock organic maturity; expulsion efficiency and fractionation; etc.). Having all of these factors does not guarantee the liquid-rich unconventional system will have sufficient production rates and ultimate recovery for an economic play, but not having one or more guarantees the liquid-rich unconventional system will be marginal or non-economic.

Selected References


Petroleum System Charge Analysis for Liquid Rich Unconventional Plays*

Michael A. Abrams
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✓ Why is not every high quality organic rich source rock an excellent liquid rich unconventional resource play?
✓ What critical petroleum systems elements are required to make an economic liquid rich unconventional resource play?

Talk Outline

1. Introduction
2. Defining Liquid-Rich Unconventional Play “shale oil”
3. Parameters Critical for Economically Successful LRU
4. Assessing Oil in Place and Movable Hydrocarbons
5. Key Take Aways

* Based on 2013 AAPG GTW keynote lecture and 2014 Unconventional Resources Technology Conference lecture.
## 1. Introduction

### Parameters Critical for Economically Successful LRU Play

#### Charge System
- **Total Organic Carbon**: how much organic carbon.
- **Organic matter type**: type of organic matter.
- **Rock maturity**: maximum temperature.
- **Migration**: expulsion versus retained hydrocarbons.

#### Production
- **Fluid properties**: original/changes with production.
- **Storage**: where is hydrocarbon stored.
- **Flow**: rock permeability, porosity, and pore pressure.
- **Completions**: rock properties critical to fracability.

#### Economics
- **Drilling cost**: location and depth.
- **OOIP**: how much oil is in place.
- **EUR**: how much can you produce and at what rate.

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scope</th>
<th>Thickness</th>
<th>Depth</th>
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</thead>
<tbody>
<tr>
<td><strong>SIZE</strong></td>
<td>Shows</td>
<td>OOIP</td>
<td></td>
</tr>
<tr>
<td><strong>RICHNESS</strong></td>
<td>Level of Maturity</td>
<td>TOC</td>
<td></td>
</tr>
<tr>
<td><strong>SOURCE</strong></td>
<td>Oil Quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HC</strong></td>
<td>Permeability</td>
<td>Porosity</td>
<td>Pressure</td>
</tr>
<tr>
<td><strong>FLOW</strong></td>
<td>Thickness</td>
<td>Definition</td>
<td></td>
</tr>
<tr>
<td><strong>COMPLETION</strong></td>
<td>Mineralogy</td>
<td>Young's Modulus</td>
<td>Poisson's Ratio</td>
</tr>
<tr>
<td></td>
<td>Stress</td>
<td>Seals</td>
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</tr>
</tbody>
</table>

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Modified from Craig Rice, Apache

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**1. Introduction**

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Technical Distinctions between Gas and Liquid Systems

Size matters (at least in gas versus liquids)

- Size of molecule relative to pore throat size is critical.

Methane CH₄
3.75 Å

Octane C₈H₁₈
length 13.17 Å
height 4.85 Å

Thermal Maturity Window

- GAS – Overmature versus LIQUIDS – Mid to Late Mature

Molecular Interactions: Gas versus Liquid Forces

- gases – molecular interactions (Van der Waals) versus liquids – viscous.

Shale gas learning's are of limited use in liquid rich unconventional system.
2.0 Defining Liquid-Rich Unconventional Play

“fine-grained rock acting as both hydrocarbon* source and reservoir, or a low permeability reservoir with inter-bedded or juxtaposed organic-rich shale with liquid hydrocarbon potential”

Abbots (2014)

Broader Definition: Reservoir which requires significant stimulation to provide economic liquid production rates.

End Members

- **Eagle Ford** (porous mudstone):
  - source = reservoir/no migration.

- **Bakken** (hybrid/interbedded):
  - source ≠ reservoir/migration.

From Bohacs et al. (2013)

- Source versus reservoir → same, juxtaposed, or off structure charge?

*Hydrocarbon*: to include hydrocarbon and non-hydrocarbon (NSO) compounds.
3.0 Parameters Critical Economically Successful LRU Play

3.1 Type and Amount of Organic Matter

**Total Organic Carbon (TOC)**

- **What is Total Organic Carbon?**
  - Reactive kerogen
  - Inert Kerogen
  - Bitumen (generated HC)

- **How do you measure TOC?**
  - **Leco**: Rock pulverized, sieved, reacted with hydrochloric acid, dried, accelerator added, and CO2 quantitatively measured.
  - Calculated from programmed pyrolysis:

\[
\text{SRA TOC} = k \times \frac{(S1 + S2) \times S4}{10}
\]

Where \( k = 0.83 \) (the average carbon content of hydrocarbons based on atomic weight)

- **S1**: hydrocarbons present in a free or adsorbed state during pyrolysis volatilized at moderate temperatures [mg/g rock].
- **S2**: hydrocarbons and hydrocarbon-like compounds which are set free at increased temperatures [mg/g rock].
- **S4**: residual carbon obtained from SRA plus TOC oxidation oven. The residual fraction (S4) oxidized dead carbon and does not contain potential to generate hydrocarbons.

→ Leco & SRA DO NOT provide same result!

**Abrams (in press)**

**Leco vs SRA**

From Peters
3.1 Type and Amount of Organic Matter, cont.

Factors that impact TOC measurement:

- **Organic maturity.**
  - TOC will decrease with maturity
  - Bitumen vs kerogen

- **Generated (free) hydrocarbon:**
  - Heavier free hydrocarbons (> C_{50}) and non-hydrocarbons (resins, asphaltenes) will vaporize/crack higher temperatures.

- **Carbon based mud additives:**
  - Oil based mud (diesel, crude, synthetic,..).
  - Carbon lost circulation (BaraBlok, SteelSteal,..)

What is minimum TOC required?

No right answer.......... but TOC_o less than 1.5% is a general cut off used by many.

- **TOC critical in evaluating liquid rich unconventional plays.**
- **Important to understand how and what you are measuring.**
3.1 Type and Amount of Organic Matter, cont.

**Organic Matter Type** (quality)

- Organic matter type determination?
  - ✓ programmed pyrolysis (HI, OI,...).
  - ✓ visual kerogen analysis (VKA).

- Key hydrocarbon information:
  - ✓ Generation kinetics (timing).
  - ✓ Product type and phase (oil versus gas).
  - ✓ Molecular composition (SARA).

*OMT impacts hydrocarbon phase and type, as well as movable versus immobile hydrocarbons.*
3.2 Organic Maturity

- What is optimal maturity window?
- How to measure organic maturity?
  - Vitrinite Reflectance – $Ro$ or $VR$.
  - Programmed pyrolysis - $T_{max}$.
  - In situ generated hydrocarbons.
- Potential issues Vitrinite Reflectance:
  - proper QC (number in-situ VR,……).
  - vitrinite reflectance suppression.
  - reworked vitrinite material.
  - absence vitrinite, age or deposition.

From Jarvie

Lo (1993)
3.2 Organic Maturity, cont.

Programmed Pyrolysis Tmax

Temperature at peak hydrocarbon generation (S2) during pyrolysis [°C].

- Potential issues with Tmax:
  - different instruments (Rock eval/SRA).
  - conversion Tmax to VRE.
  - limited to immature to mature rocks.
  - variability and interpretation.

* Ro (calculated) = (0.0180)(Tmax) – 7.16
  Jarvie et al (2001)
3.2 Organic Maturity, cont.

- **Maturity from in-situ hydrocarbons.**
  
  *Diamondoids* and other compounds can be used as proxy for direct measurement of oil cracking (level of organic maturity).

- **Potential issues:**
  - impact of extraction.
  - volatile loss with cuttings.
  - migrated fluids (not in-situ).

### Table: Organic Maturity

<table>
<thead>
<tr>
<th>Maturity</th>
<th>VRE range</th>
<th>Tmax range</th>
<th>Transformation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immature</td>
<td>Less than 0.5</td>
<td>Less than 435°C</td>
<td>0</td>
<td>No S1 (free hydrocarbons) present.</td>
</tr>
<tr>
<td>Early Mature</td>
<td>0.5 to 0.7</td>
<td>435°C - 440°C</td>
<td>10</td>
<td>Early bitumen with characteristics consistent with low maturity hydrocarbon generation.</td>
</tr>
<tr>
<td>Mature</td>
<td>0.7 to 1.0</td>
<td>440°C - 450°C</td>
<td>50</td>
<td>Molecular composition consistent with full maturity oil and gas.</td>
</tr>
<tr>
<td>Late Mature</td>
<td>1.0 to 1.3</td>
<td>450°C - 470°C</td>
<td>90</td>
<td>Molecular composition consistent with late maturity oil and gas.</td>
</tr>
<tr>
<td>Overmature</td>
<td>1.3 to 1.8</td>
<td>470°C plus</td>
<td>100</td>
<td>Predominantly light oil and gas generation.</td>
</tr>
<tr>
<td>Supermature</td>
<td>1.8 plus</td>
<td>NA</td>
<td>100</td>
<td>Maturity calculation very difficult in super mature rocks.</td>
</tr>
</tbody>
</table>

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*Organic maturity impacts generation timing, fluid type and phase as well as organic porosity.*
3.3 Expulsion Efficiency/Secondary Reactions

- How much generated hydrocarbon is retained?
  - Modeling programs % pore volume or weight.
- Which compounds remain (less mobile)?
  - Asphaltenes/Resins-Polars/Aromatics/Saturates
- Secondary reactions: minerals and organic residues → coats minerals can be resistant to maturity driven chemical change.

Other items:
- Role hydrocarbon generation micro fracturing?
- Compound fractionation during production?

*Primary migration impacts how much hydrocarbon remains within source rock and/or local reservoir as well as type of hydrocarbons.*
Primary Migration – Production Fractionation

**Bakken Produced Oil:** \(58.6\% < C_{15}\) (Locken 11-22h):

- %Sat: 50.1, %Aro: 44.0, %R: 5.9, %Asph: 0.0

<table>
<thead>
<tr>
<th>Layer</th>
<th>% Sat</th>
<th>% Res</th>
<th>% Aro</th>
<th>% Asph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Bakken Sh</td>
<td>10.6</td>
<td>18.2</td>
<td>37.3</td>
<td>34.0</td>
</tr>
<tr>
<td>Middle Bakken “B”</td>
<td>40.3%</td>
<td>35.6%</td>
<td>15.8%</td>
<td>8.4%</td>
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<tr>
<td>Lower Bakken Sh</td>
<td>11.1</td>
<td>17.4</td>
<td>36.3</td>
<td>35.3</td>
</tr>
</tbody>
</table>

Source Rock (52% Res & Asph)

Reservoir Rock (44% Res & Asph)

Produced Oil (6% Res)

UCR oils can be expected to be chemically different to oil in conventional reservoirs.

Type of fluid system will have impact on production rates;
- *Under-Saturated* (dead oil)
- *Saturated* (black to volatile oil)
- *Liquids Rich Gas* (condensate)

Fluid type driven by:
- organic matter type (source facies)
- level of maturity (thermal stress).

Petroleum changes with production:
- Production can lead to drop in pressure and change to a two phase system (liquid and gas) depending on fluid type and reservoir conditions. Two phase systems will yield higher volumes of gas relative to oil due to liquid drop out and relative permeability issues.

In-situ petroleum composition has significant impact on production rates and ultimate hydrocarbon recovery thus want to optimize fluid system prediction to maximize liquids production.
3.5 Hydrocarbon Storage

**ORGANIC POROSITY**
- Recent studies suggest organic porosity provide significant hydrocarbon storage potential in LRU systems.
- Organic porosity impacted by:
  - thermal maturity
  - organic matter type.
- **Effective porosity** requires connectivity within organic material as well as matrix (series or in parallel).
- Recent studies indicate OM connectivity is poor (Curtis et al., 2014).

![Maturity Window](image) Modified from Wan et al (2013)

How can we better understand if organic porosity is a major contributor and if not, need to examine matrix for hydrocarbon storage.

![Graph](image) Romero-Sarmiento et al. (2013)
Empirical observations indicate wells with enhanced organic porosity as seen via SEM, have higher production rates.

Liquid rich UCR core SEM images have little or no organic porosity, have very lower production rates.

Maturity is not significantly different between these two plays; impact of organic matter type and burial history on the formation organic porosity?
3.6 Flow Capacity

- Porosity and permeability play major role in reservoir flow capacity.
- Pore pressure is extremely critical (drive and phase)
- Burial history (burial rate) has significant impact on pore pressure as well as P&P.

Fluid quality and flow capacity have major impact to “swing the needle” on economics.
3.7 Rock Fracability

- **Rock mineralogy**: major impact on brittleness (ductile versus brittle).
- **Stress assessment**: regional structural regime (amount and direction).
- **Burial history**: maximum depth, burial rate, and potential uplift.

- Burial and exhumation history timing
- Thermal gradient
- Gross geologic setting
- Geomechanics properties (if available)

- Assessment of stresses ahead of drilling
- Identification of regions susceptible to fracturing
- Contributes to ‘sweet spot’ identification

- Enhanced production occurs for optimal combinations of burial and exhumation
- Relatively simple screening tool for ranking access areas

*Image courtesy of Steve Wilson*
4.0 Assessing Oil in Place and Movable Oil

- Two important measurements for evaluating LRU economics;
  - How much liquid hydrocarbon/non HC present (total volume in place oil)?
  - How much remaining oil is movable (producible with enhancement)?

- Current methodologies to evaluate Oil-In-Place (OIP):
  - Wireline log calculated petrophyiscal estimates.
  - Direct measurements from extracted hydrocarbon measurements.

- Both provide directional information on OIP but do not measure producible oil.

- **Pyrolytic Oil Productivity Index (POPI)** direct assessment of reservoir quality from residual staining on drill cuttings (Jones et al., 2007).

- Modified programmed pyrolysis to evaluate thermally distilled residual hydrocarbons.
  
  - Light Volatiles – Thermally distilled – Thermally Cracked

- **Corrected S1 programmed pyrolysis** method by Michaels et al. (2013)* determine total resource in-place and calculate recovery factors.

- Developed work flow using standard programmed pyrolysis, applies correction factor to S1 (“free” hydrocarbons) to compensate for lost hydrocarbons.

* See presentation on Wednesday
Not all organic rich oil generating source rocks will provide an economic liquid-rich unconventional petroleum system.

**Critical Petroleum Systems Elements:**

- Regionally extensive and thick organic rich oil prone source rock (critical volume).
- Source rock with sufficient thermal maturity for given organic matter type to generate significant in-situ liquid rich volumes.
- Sufficient retained hydrocarbons after primary migration (expulsion efficiency).
- Optimal in-situ hydrocarbon fluid properties for host rock type (semi volatile oil).
- Significant in-place movable hydrocarbons for economic production rates/EUR.
Having critical petroleum systems factors in place does not guarantee your liquid-rich unconventional system will have sufficient production rates and ultimate recovery for an economic play, but not having one or more guarantees the liquid-rich unconventional system will be marginal or non-economic.

**Future research needs:**

- More quantitative evaluation OMT.
- Better understanding retained hydrocarbons and in-situ organic-matrix interactions.
- Significance organic porosity in LRU plays.
- Measure producible hydrocarbons vs OIP.

**Acknowledgments**

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