Components and Processes Impacting Production Success from Unconventional Shale Resource Systems*

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Abstract

Unconventional shale resource systems can provide massive energy reserves for gas and oil if developed properly and soundly. Development of these systems has evolved rapidly over the past decade in North America, although it took 30 years to reach such a level.

The key component of an unconventional system is the source rock itself. Thus, basic factors such as shale thickness, porosity, permeability, mineralogy, rock mechanics, organic richness, kerogen type, and oil/water/gas saturation are important variables. An unconventional shale resource system may be described as a continuous organic-rich source rock with low porosity and permeability with or without juxtaposed (overlying, interbedded, or underlying) organic-lean tight rock units.

Unconventional thermogenic shale gas resource systems are divided into overlapping categories. There are highly productive organic and silica-rich mudstones that are most often gas-window mature, but there are also some productive systems that are oil-window mature producing high BTU gases. Systems dominated by a gas-window mature (>1.00%Roe), organic-rich mudstone typically have 30-80% of their petroleum storage in organic porosity. Hybrid systems have both organic and matrix porosity and will usually be far more productive as a result of higher storage capacity.

Unconventional shale oil resource systems, while dominantly clay and organic-rich mudstones have produced significant amounts of oil (e.g., Barnett Shale in the oil window), systems with juxtaposed, organic-lean carbonates have proven more successful (e.g., Eagle Ford Shale, Bakken Formation, and Niobrara Shale). There are also fractured shale oil resource systems and even high-porosity, high-permeability shale systems, including the Miocene Monterey Shale in California, and fractured Upper Bakken Shale fields in the Williston Basin, North Dakota. While silica content remains important for rock brittleness, the source of silica, whether biogenic or detrital, becomes very important as biogenic silica will result in adsorption of oil to organic matter associated with the biogenic silica. In this case there is a tight, albeit brittle rock, but there is also strong adsorption of oil components, especially polar constituents, such as the resin and asphaltene

fractions that have not yet been cracked to lighter hydrocarbons in the oil maturity window.

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Wildcat Technologies

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- **Saudi Aramco and Aramco Services Corp.**

  Their patented POPI technique is enhancing the understanding and completion of both conventional and unconventional reservoir systems.

Talk Outline

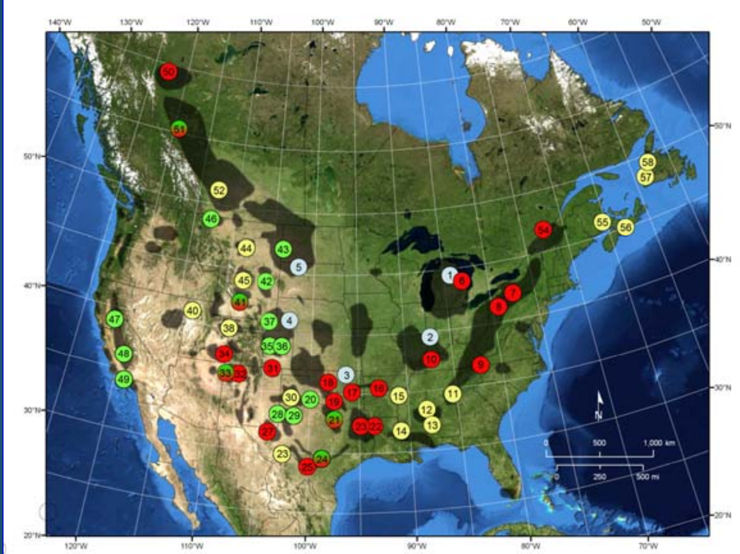
- Introduction
- Components and Processes Affecting Shale Resource Production
  - Source rock generation and organic porosity development
  - Adsorption and its role in retention, storage, and expulsion fractionation
  - Oil crossover effect (oil saturation index)
  - Producible oil index (oil saturation less adsorption indices)
- Summary of all organic, inorganic, core, geological and geophysical points

General Comments

- History of shale resource plays
  - 1800s first shale gas well in Fredonia, NY
  - Early 1900s to present Monterey Shale oil wells
  - 1980s to present Antrim Shale biogenic gas wells
- History of Stimulation
  - First stimulation in 1957
  - Over a million stimulated wells
  - 1980s to present -over 45,000 high energy stimulations on shale wells
- Mis-reporting of ground water contamination
  - The first information spits out condemnation, the facts prove the condemnations incorrect
  - e.g., water wells in Parker County, TX were contaminated with gas most likely for several millions of years prior to Range Resources drilling and stimulating the Barnett Shale; case dismissed – no contamination by Range proven by geochemistry of gases
- Economic impact: jobs, revenues
  - Eagle Ford Shale will create tens of thousands of jobs over the next decade
  - It will also generate billions in revenues for everyone: drillers, landowners, state/local governments, schools, citizens, ancillary service industries, and so forth

North American Shale Resource Plays

(red=gas, green=oil, light blue=biogenic gas, yellow-unproven to date)

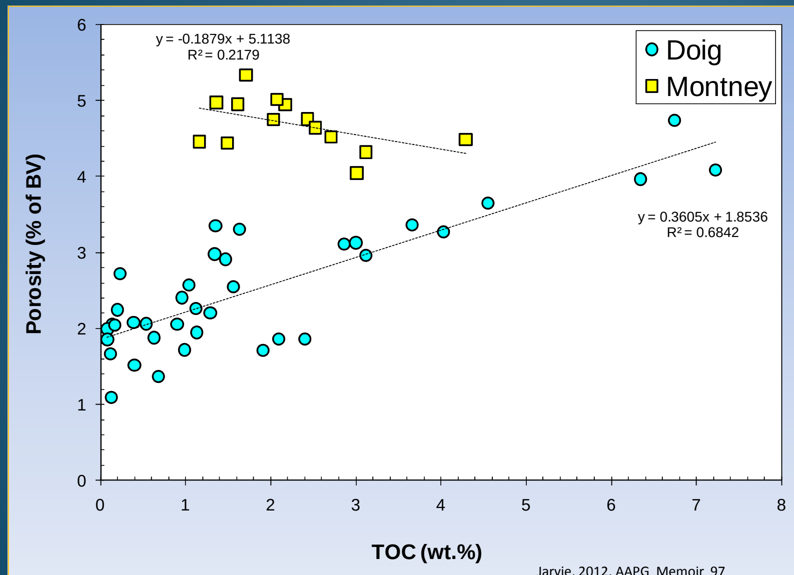


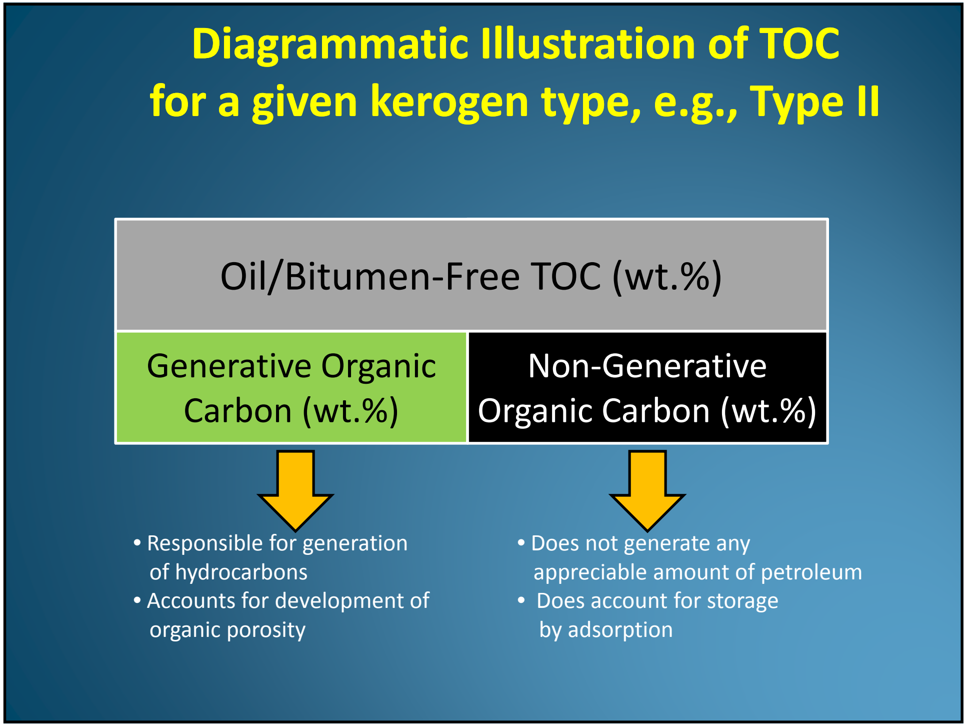
Jarvie, 2012, AAPG Memoir 97

What is a Shale Resource System?

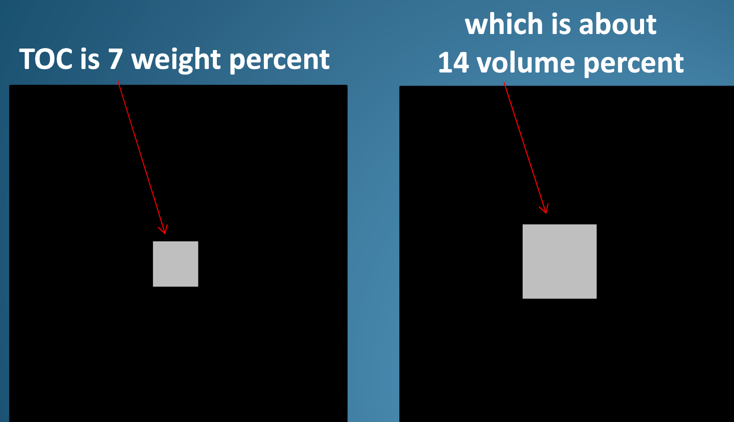
A shale resource system is
any continuous organic-rich source rock
with or without juxtaposed organic-lean lithofacies
that can made to produce naturally generated petroleum
via high energy stimulation.

Matrix and Organic Porosity




Diagrammatic Illustration of TOC
for a given kerogen type, e.g., Type II
Oil/Bitumen-Free TOC (wt.%)
Generative Organic Carbon (wt.%)
Non-Generative Organic Carbon (wt.%)
• Responsible for generation of hydrocarbons
• Accounts for development of organic porosity
• Does not generate any appreciable amount of petroleum
• Does account for storage by adsorption

Conversion of organic carbon (TOC) in wt.% to vol.%



Formation of Organic Porosity from Generative Organic Carbon

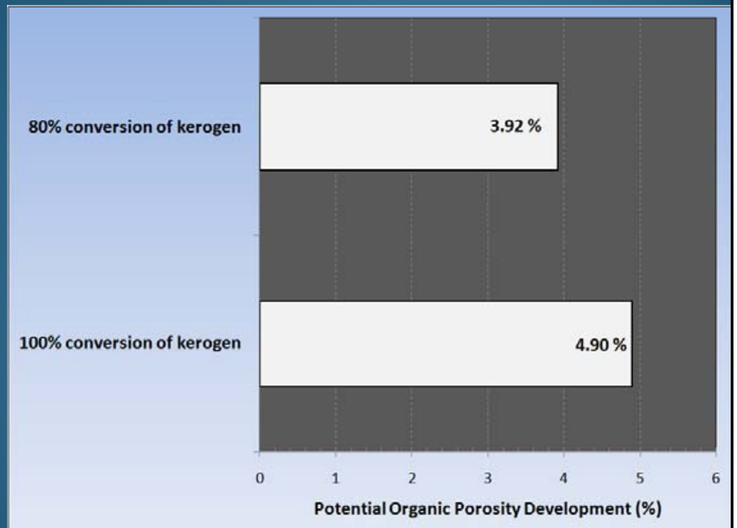
Assumptions:

7.00 wt.% TOC_o

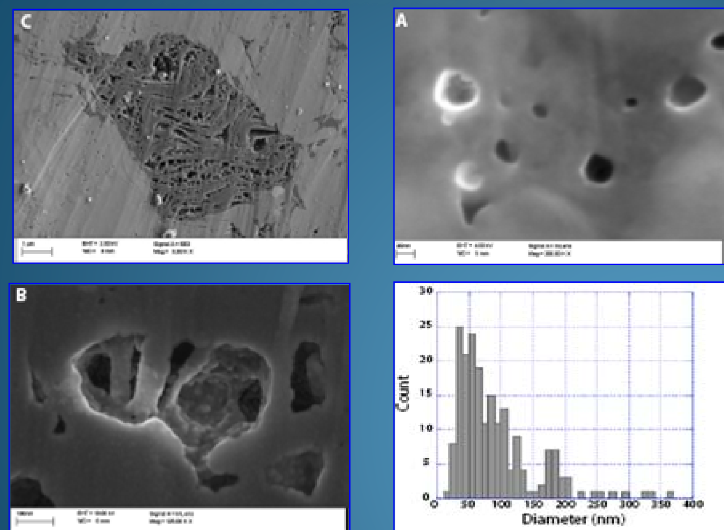
14.00 vol.% TOC_o

TOC_o is 37% GOC

Kerogen density is:
- 1.1 g/cc GOC
- 1.4 g/cc NGOC



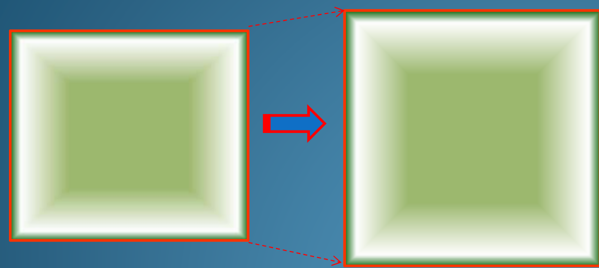
Organic Porosity Development in the Barnett Shale



Loucks et al., 2009

Why are no organic pores typically seen in the oil window?

Solubility of oil in kerogen and kerogen expansion



Supporting evidence consists of (1) oil extractable from rock and even isolated kerogen, and (2) aromatic fractionation in Bakken Shales versus expelled Bakken oils (Jarvie et al., 2011). Literature reports fractionation of aromatics from saturated hydrocarbons in kerogen swollen with different solvents (Ertas et al., 2011)

Fractionation of Generated Oils
very important in hybrid systems

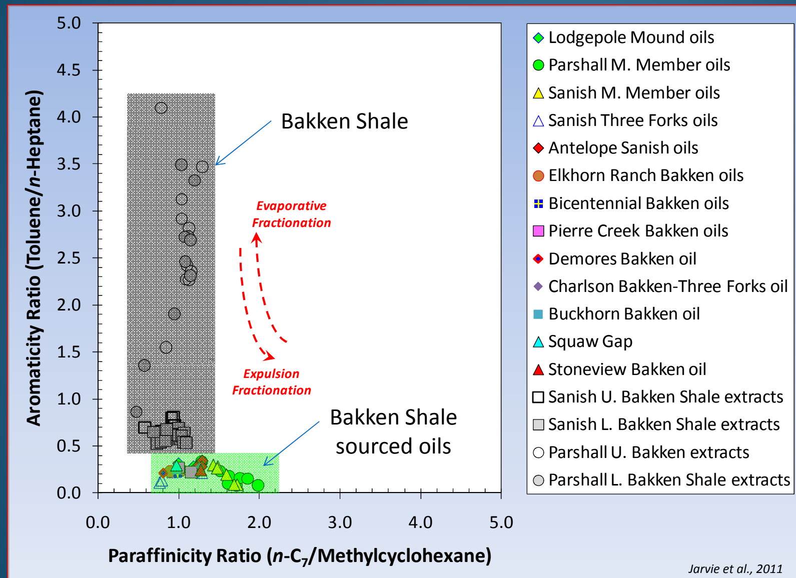
	% Sats	% Aros	% NSOs	% Total
Composition of Generated	55	19	26	100
Composition of Retained	44	12	44	100
Composition of Expelled	67	26	7	100

Adsorption:
ca.10 g petroleum per 100 g TOM

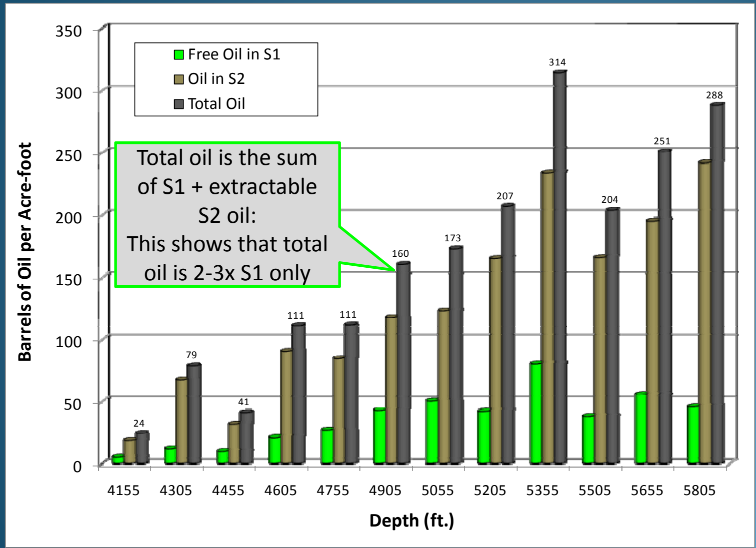
Expelled:	60% of saturates
Expelled:	68% of aromatics
Expelled:	14% of resins
Retained:	40% of saturates
Retained:	32% of aromatics
Retained:	86% of resins

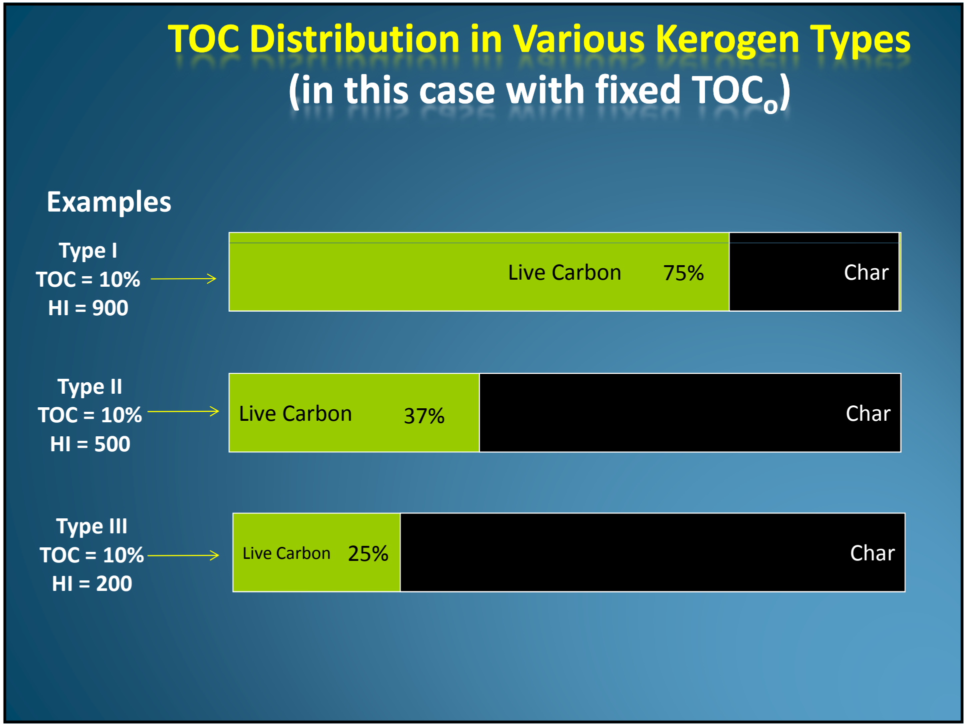
Sandvik et al., 1992

For example, Ertas at al., (2006) data suggests fractionation of aromatics, which occurs in a comparison of Bakken Shale extracts versus Bakken sourced oils

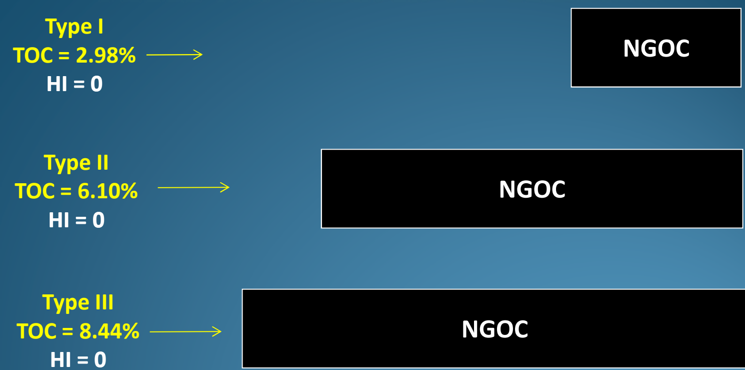


Extraction of Whole Rock Samples often yields additional oil sorbed in rock matrix and kerogen; kerogen and asphaltnes sorb oil too




TOC Distribution in Various Kerogen Types
(in this case with fixed TOC$_o$)
Examples
Type I
TOC = 10%
HI = 900
Live Carbon 75%
Char
Type II
TOC = 10%
HI = 500
Live Carbon 37%
Char
Type III
TOC = 10%
HI = 200
Live Carbon 25%
Char

Spent TOC (only NGOC remains)

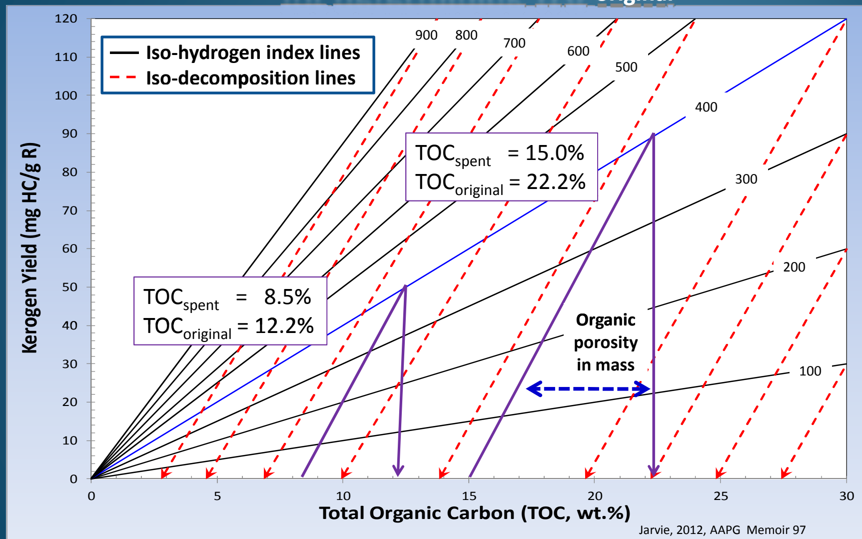


$TOC_{original}$	$HI_{original}$	GOC	NGOC	TOC_{spent}
10.00	900	76.5%	2.35	2.98
10.00	500	42.5%	5.75	6.10
10.00	200	17.0%	8.30	8.44

Percent GOC is HIoriginal / 1177 (assumes 85% carbon in petroleum/bitumen)
GOC is generative organic carbon
NGOC is non-generative organic carbon
TOC_{spent} includes additional char formation

Nomograph of Iso-Decomposition Lines with iso-hydrogen indices

for determining $TOC_{original}$

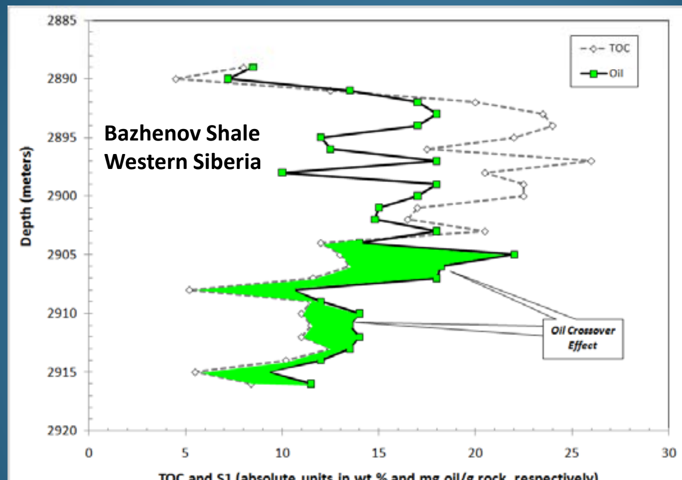


Key to Producible Shale Oil Resource System?
when high oil saturations are indicated –
the oil crossover effect

Utilizing the "Oil Crossover Effect":

When the Oil Saturation Index > 100 mg oil/g TOC,

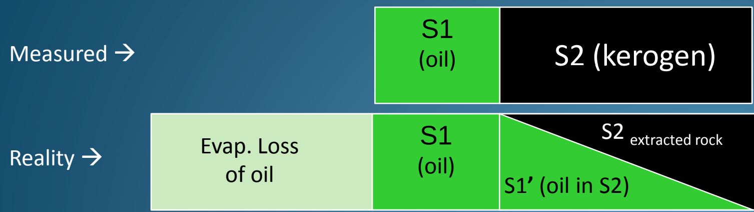
producible oil is present.



Data from Lopatin et al., 2003

Jarvie, 2012, AAPG Memoir 97

Oil Content in Rock Sample as measured by thermal extraction



Overlap of free oil and oil carried over into S2
This is a function of oil type and isolated organic pores

Total Oil = $(S1_{WR} - S1_{extracted\ rock}) + (S2_{whole\ rock} - S2_{extracted\ rock})$ + E.L.

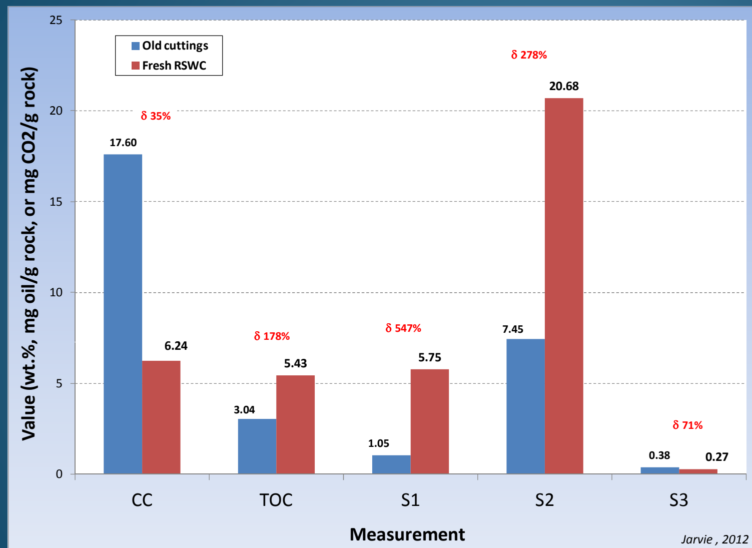
Evaporative Losses = S1 x (GC Fingerprint produced oil / GC Fingerprint of extracted oil)
This technique also allows prediction of GOR on shale (rock) samples.

Factors Affecting S1

- Type of sample (cuttings, SWC, core)
- Type of lithofacies (shale, carbonate, sandstone)
- Analytical instrument utilized for analysis
- Sample handling and processing (esp. heating)
- Oil-based mud (OBM) or organic additives to drilling fluids

Change in Various Geochemical Measurements due to age, sample type

(data from 1980s well and new offset well)



Parshall Field, Williston Basin Bakken Shale, Reservoir and Oil Fingerprints

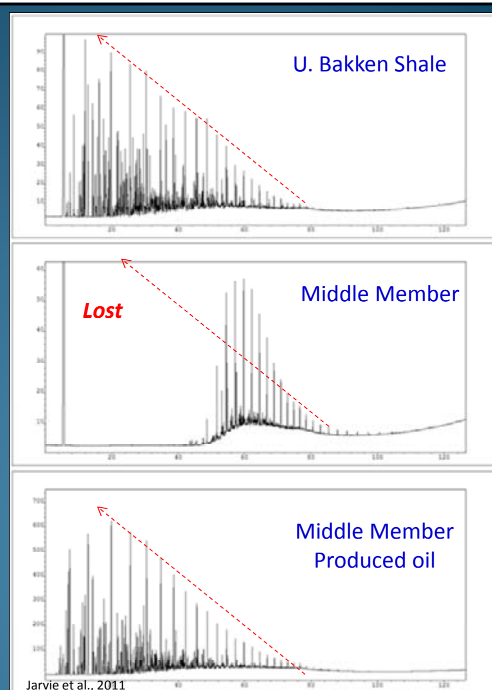
Key Observations

1. U. Bakken Shale has lost very little oil, may be less than the produced dead oil sample

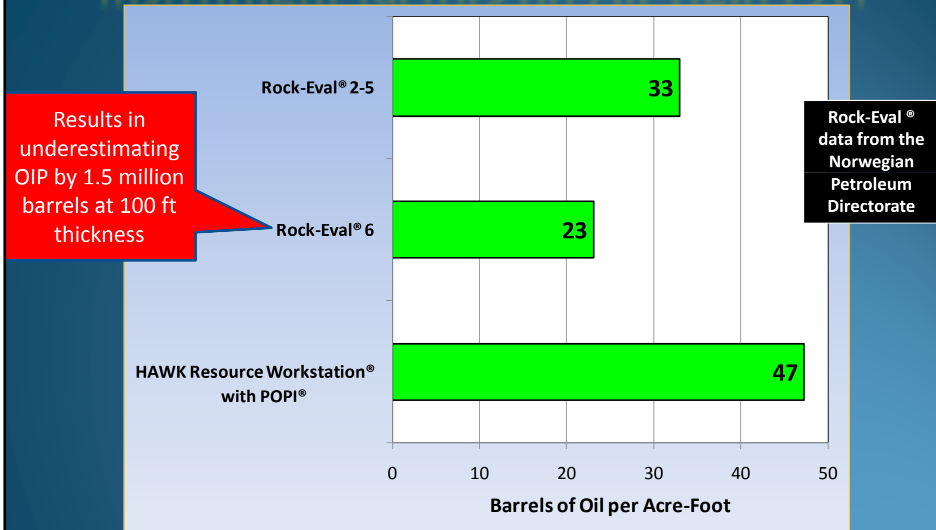
2. Middle Member has lost most hydrocarbons less than C15

<u>Key Point</u>

- Shale holds the oil very tightly, whereas the dolomitic member retains very little light oil



Instrument factors on Oil Yield (S1)



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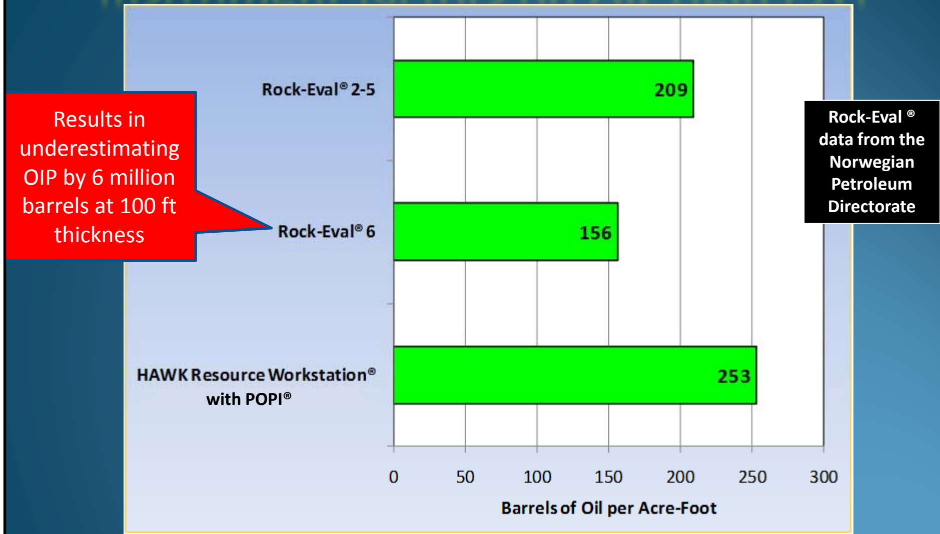
HAWK Resource Workstation® is a registered trademark of Wildcat Technologies, Humble, Texas

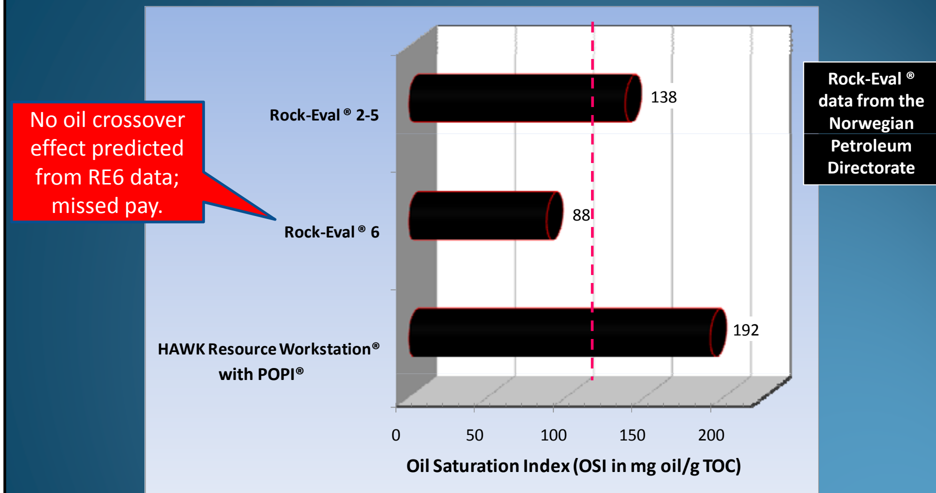
POPI® is a patented techniques and registered trademark of Saudi Arabian Oil Company.

Instrument factors on Oil Yield (S1)



Low Oil Measurements on RE-6 Underestimate OOIP

and also crossover effect resulting in potentially missed pay



Claims that RE-2 and RE-6 Pyrolysis Yields are different

<u>not substantiated</u> by published IFP data

RE-2 and RE-6 data comparison in Behar et al., 2001. These data show high degree of correlation essential for compatibility of Rock-Eval® data.

Behar et al., 2001

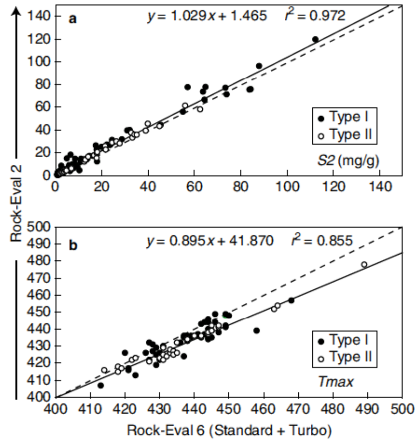


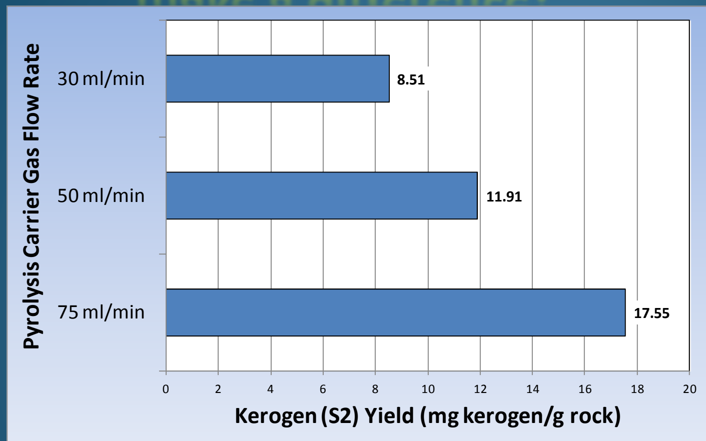
Figure 13

Correlation between Rock-Eval 2 and Rock-Eval 6 data: (a) *S2* (mg/g); (b) *Tmax*.

Does carrier gas make a difference? depends on analysis…

- RE-6 uses nitrogen only
  - Advantages
    - Less likely to leak
      specific gravity 7x helium
    - Can be generated
  - Disadvantages:
    - Lower thermal conductivity
      5.7x lower than helium
      Higher Tmax correction
      True Tmax 40° higher at 25°C/min
      - Important for kinetic measurements
- **HAWK®** uses either nitrogen or helium
  - Nitrogen for routine analysis including well site
  - Helium for kinetics

Does Carrier Gas Mass Flow make a difference?



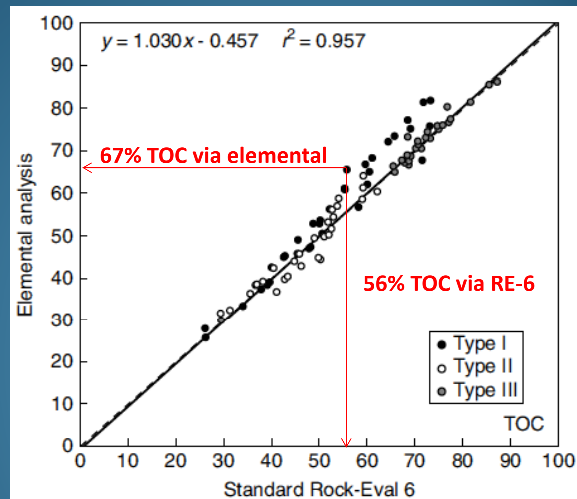
- **HAWK®** uses electronic mass flow controllers <u>independent</u> of gas pressure
- SR Analyzer™ uses manual pressure regulators to control gas flow; dependent on gas pressure <u>only which can vary considerably</u>

RE2, RE6, Leco, and Elemental organic carbon analysis (TOC)

TOC is consistent among all analytical techniques and <u>no</u> errors result in interpretive differences among kerogen types or source rock potential (the GOC portion of TOC is more important for generation, whereas NGOC is more important for organic storage).

Results from Behar et al., 2001, show that RE-6 TOC data can vary from elemental analysis by upwards of 10 wt.% TOC.

Leco TOC is inherently the best method for TOC measurements.

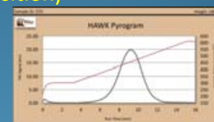


Behar et al., 2001

Assessing Shale Resource Systems

HAWK Resource WorkStation®

1. Designed for both laboratory and well site use
2. Determine oil carryover (oil in kerogen peak)
3. Determine lost oil due to evaporation from storage, handling, processing
4. Assess oil quality (API gravity, viscosity, GOR, sulfur, gas composition)
5. Determine TOC, total carbon, and carbonate carbon
6. Predict organic porosity
7. Determine OOIP or GIP (equivalency)
8. Built-in shale resource comparative database
9 Built-in kinetics profiles for transformation rate prediction

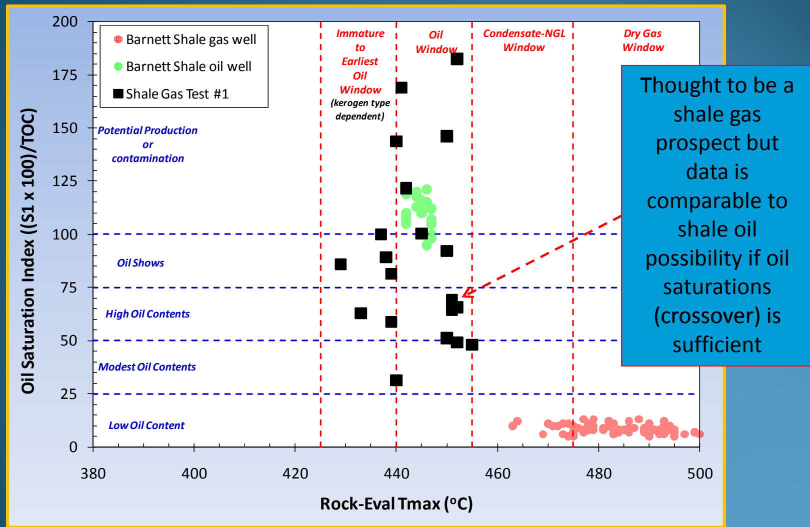


New ***HAWK*** ®
Resource WorkStation
Wildcat Technologies
Available Jan 2013

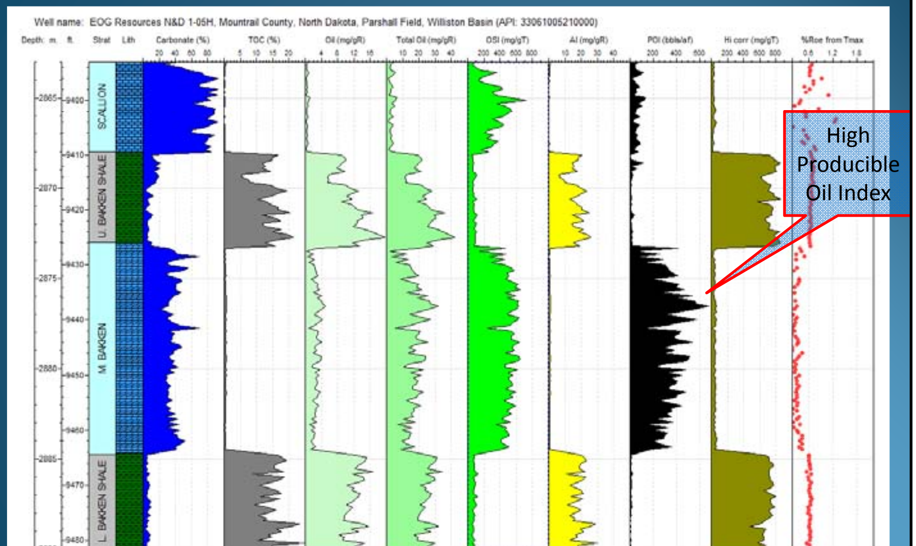
Total Oil
S1’ | S1 | S1” | Kerogen (S2)
OOIP | GOC | NGOC
Total Carbon
Carbonate Carbon
Total Sulfur
Gas/MS

HAWK Resource Workstation

comparison of resource with analog systems



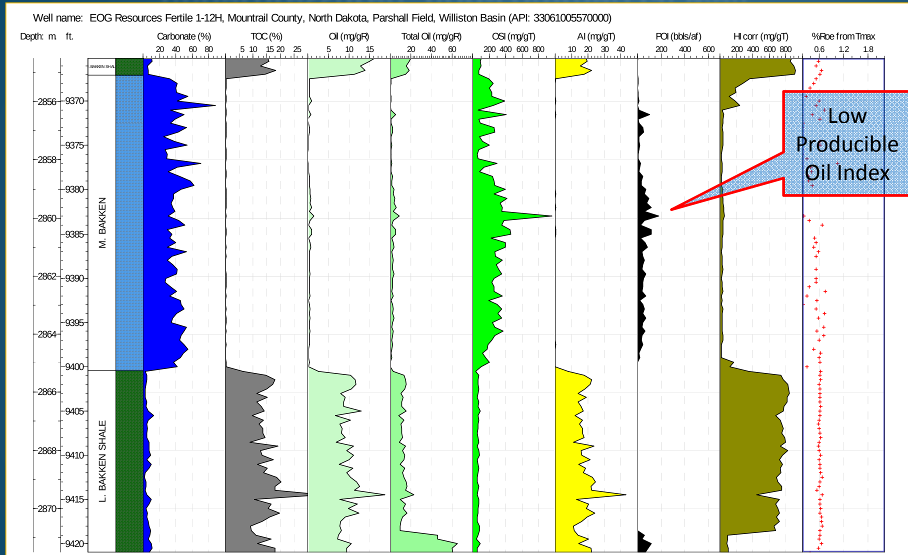
EOG Resources N&D 1-05H, Parshall Field
overpressured, commercial well



Jarvie et al., 2011

EOG Resources Fertile 1-12H

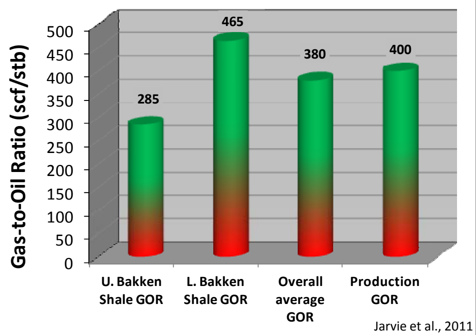
underpressured, non-commercial well



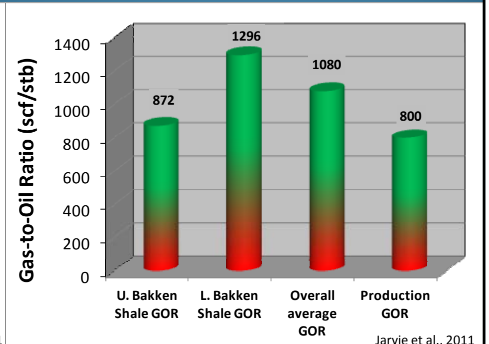
Jarvie et al., 2011

Added Value of Predicted GOR values directly on shale samples

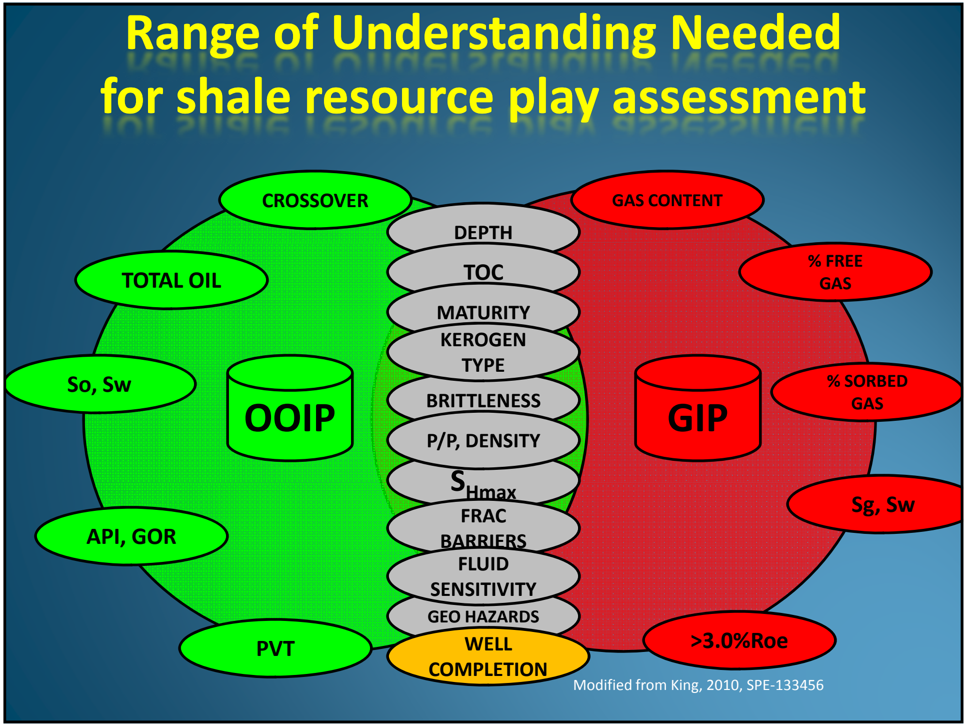
Parshall Field
Predicted GOR values



Sanish Field
Predicted GOR values



This prediction requires a GOR-GC analysis that uses C_6 and C_7 hydrocarbons that are used to predict GOR from organic-rich shale samples


Range of Understanding Needed
for shale resource play assessment
CROSSOVER
TOTAL OIL
So, Sw
OOIP
API, GOR
PVT
DEPTH
TOC
MATURITY
KEROGEN TYPE
BRITTLENESS
P/P, DENSITY
S_{Hmax}
FRAC BARRIERS
FLUID SENSITIVITY
GEO HAZARDS
WELL COMPLETION
GAS CONTENT
% FREE GAS
GIP
% SORBED GAS
Sg, Sw
>3.0%Roe
Modified from King, 2010, SPE-133456

For information about the

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