

Utilizing Pressurized Rotary Sidewall Cores for the Determination of Pore Fluid Total Material Balance and Characterization of Bulk Fluid Hydrocarbons*

Chad Hartman¹

Search and Discovery Article #42364 (2019)**

Posted April 1, 2019

*Adapted from oral presentation given at 2019 AAPG Middle East Region GTW, Regional Variations in Charge Systems and the Impact on Hydrocarbon Fluid Properties in Exploration, Dubai, UAE, February 11-13, 2019

**Datapages © 2019 Serial rights given by author. For all other rights contact author directly. DOI:10.1306/42364Hartman2019

¹Weatherford Laboratories, Golden, Colorado, United States (chad.hartman@weatherford.com)

Abstract

Once the general vertical location, quality, and character of a target reservoir are identified through mud gas analysis and subsequent petrophysical logging of the wellbore, pressurized rotary sidewall cores can be obtained from wireline deployable tools and evaluated within a relatively rapid timescale. Through depressurization and subsequent extraction (solvent and/or thermal methods), one can obtain pore fluid total material balance (stock tank) for oil-in-place and gas-in-place estimates, bulk hydrocarbon compositional and geochemical character, gas-oil or condensate-gas ratios, and equation-of-state thermodynamic models which allow for predictions of in-situ fluid phase behavior. Armed with these data an operator can rank stacked pay, make informed decisions about lateral well placement, and formulate reasonable estimates of EOR and well performance.

References Cited

Egenhoff, S.O., A. Van Dolah, A. Jaffri, and J. Maletz, 2011, Facies Architecture and Sequence Stratigraphy of the Middle Bakken Member, Williston Basin, North Dakota, *in* L. Robinson, J. LeFever, and S. Gaswirth (eds.), Bakken-Three Forks Petroleum System in the Williston Basin: Rocky Mountain Association of Geologists, Guidebook, p. 27-47.

Lasater, J.A., 1958, Bubble Point Pressure Correlations: Journal of Petroleum Technology, SPE-957-G, v. 10/5, p. 65-67.
doi.org/10.2118/957-G.



AAPG

Advancing the World of Petroleum Geosciences.

Utilizing Pressurized Rotary Sidewall Cores for the Determination of Pore Fluid Total Material Balance and Characterization of Bulk Fluid Hydrocarbons

Chad Hartman
Chief Technical Advisor
Weatherford Laboratories

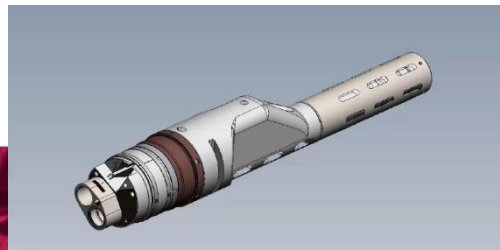


AAPG

Advancing the World of Petroleum Geosciences.

Commercially Available Pressurized RSWC Technology

- Rated to 20k psi and 400 °F.
- Holds 10 - 12 RSWCs which are in pressure communication with each other.
- Can be configured with or without P & T gauges (down hole assembly and/or internal to the pressure vessel itself).
- Can be configured with or without N₂ ballast to reduce pressure loss due to temperature effects.
- Can be transported “live” for analysis and processing under controlled laboratory conditions.



Photographs courtesy of Halliburton



AAPG

Advancing the World of Petroleum Geosciences.

- RSWCs are only as representative of the reservoir as is the skin of the wellbore.
 - Best in tight rocks ($< 10 \mu\text{d}$).
 - Active mud weight control is recommended to avoid filtrate invasion.
- Single pressurized vessel. Therefore all RSWCs are in pressure communication with one another.
 - Evaluate logs prior to selecting target zone.
 - Best to consider the tool to contain a single sample composed as 10 parts.
- Base fluid used for drilling mud can impact rock and data quality.
 - A small volume ($\sim 10 \text{ ml}$) of mud unavoidably gets trapped in the tool.
 - When targeting liquid hydrocarbons OBM can cause complications in data interpretation.
- Tool packing fluid (a perfluorocarbon) is compressible and possesses a temperature dependent density (1.88 g/cm^3 at 60°F to 1.68 g/cm^3 at 220°F).
 - Tool pressure under standard laboratory conditions is typically only a fraction of initial sealing pressure.
 - Once the bubble point or dew point is crossed the fluid phase transition is irreversible.



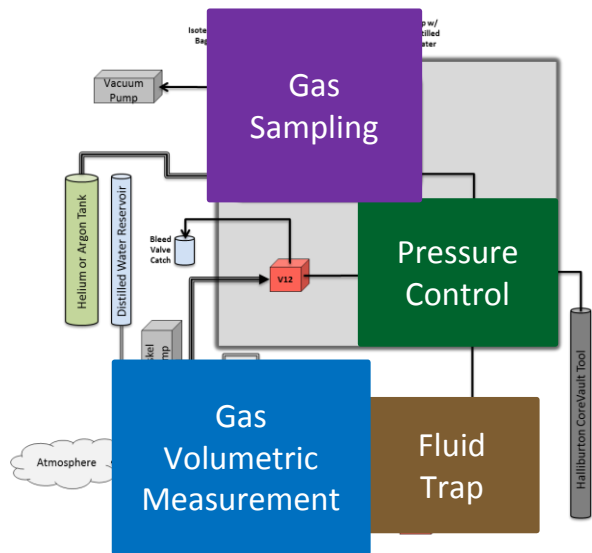
Photographs courtesy of Halliburton



AAPG

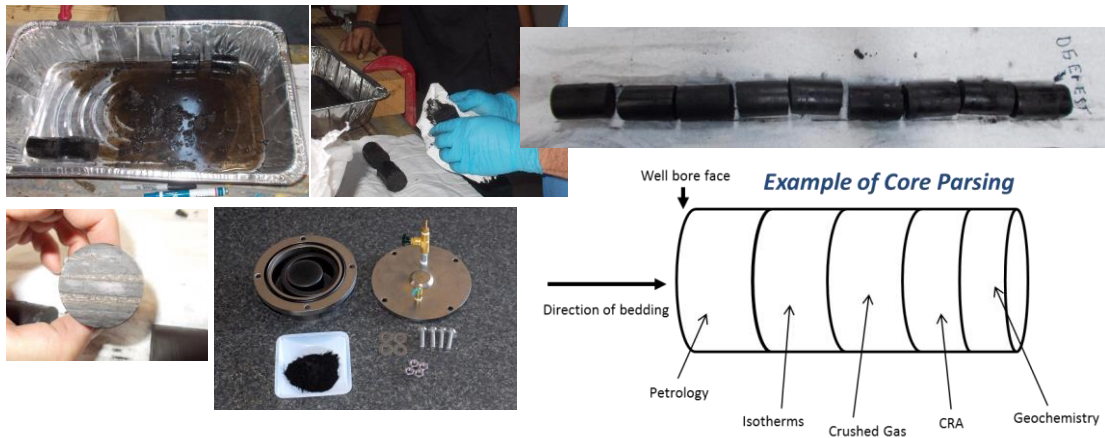
Advancing the World of Petroleum Geosciences.

- The tool is systematically depressurized under controlled conditions.
- Gas volumes are quantitatively measured.
- Gas samples are periodically captured throughout the degassing process for compositional and isotope geochemical analysis.



Tool Depressurization & Initial Core Processing

- Once depleted of all measurable gas the RSWCs are extruded and all annular fluids are collected.
- Cores are quickly wiped clean, inventoried, weighed, labeled, and photographed.
- All collected fluids (fluid trap and internal annular space) are placed in a nonreactive air tight container (typically ~ 500 ml).
- Whole core tests such as benchtop NMR analysis are performed first followed by bulk volume determination. End trims are then taken to generate composite samples for all subsequent analyses.





AAPG

Advancing the World of Petroleum Geosciences.

Gas Phase Fluid Evaluation

$$G_t = \left(32.0369 \frac{V_g}{m_t^c} \right) + G_c$$

$$GIP = 1359.7 Ah \rho_b G_t$$

where:

G_t total RSWC pressure core tool gas content, scf/ton

V_g gas volume measured from the tool, cm^3

m_t^c total sample mass of all RSWCs, g

G_c crushed gas content, scf/ton

GIP gas-in-place, scf

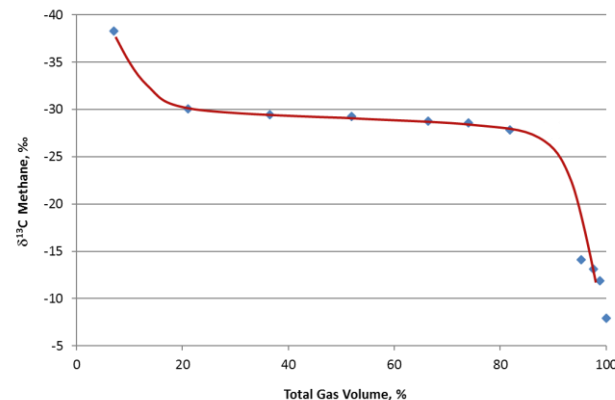
A area, acres

h reservoir thickness, ft

ρ_b CRA bulk density determined from the composite RSWC sample, g/cm^3

C1 Mole %	C2 Mole %	C3 Mole %	Total Volume %
99.72	0.28	0.00	4.39
99.88	0.11	0.01	5.53
99.15	0.84	0.01	16.65
98.78	0.99	0.23	28.84
98.91	1.07	0.01	41.04
98.59	1.19	0.23	52.42
98.69	1.29	0.02	58.38
98.59	1.40	0.02	64.60
98.49	1.49	0.02	70.81
88.10	10.71	1.19	75.24
83.46	15.44	1.11	77.08
78.79	19.52	1.69	78.04
53.82	44.15	2.02	78.94
39.75	50.05	10.20	100.00

- Both the molecular composition of the gas and isotopes of each component fractionate with depletion.
- Fractionation is driven by differences in diffusion rates, adsorption potential, and solubility in brine and/or liquid phase hydrocarbons.

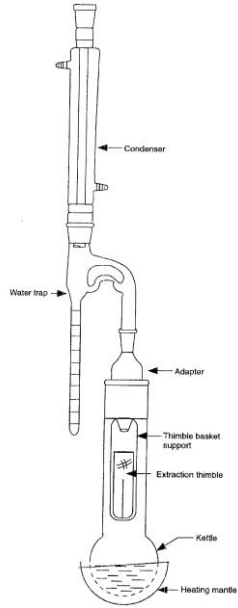




AAPG

Advancing the World of Petroleum Geosciences.

- Dean-Stark toluene extraction removes free water, bound water, and oil (including bitumen).
- Water is measured. Oil is calculated by weight difference.



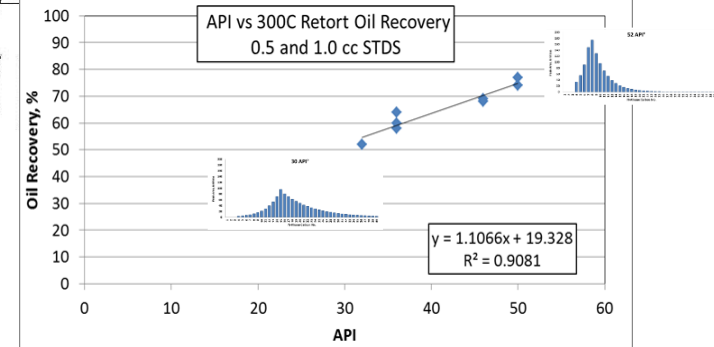
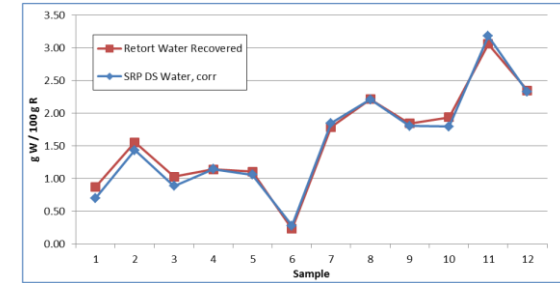
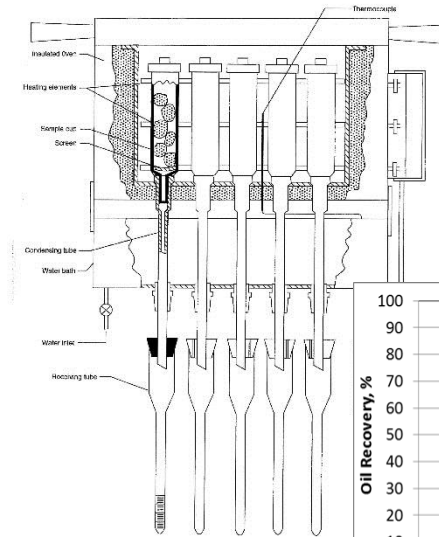
$$v_o = \frac{m_{pre} - (m_{post} + m_{water})}{\rho_o}$$

where:

v_o volume oil, cm^3
 m_{pre} pre-test sample mass, g
 m_{post} post-test sample mass, g
 m_{water} extracted water mass, g
 ρ_o assumed oil density, g/cm^3

“Routine” Fluid Volumetrics

- 300°C thermal extraction. Volatilized compounds are condensed and captured (water and oil).
- Fraction of oil recovery (relative to solvent based methods) is proportional to API° (i.e. MW).



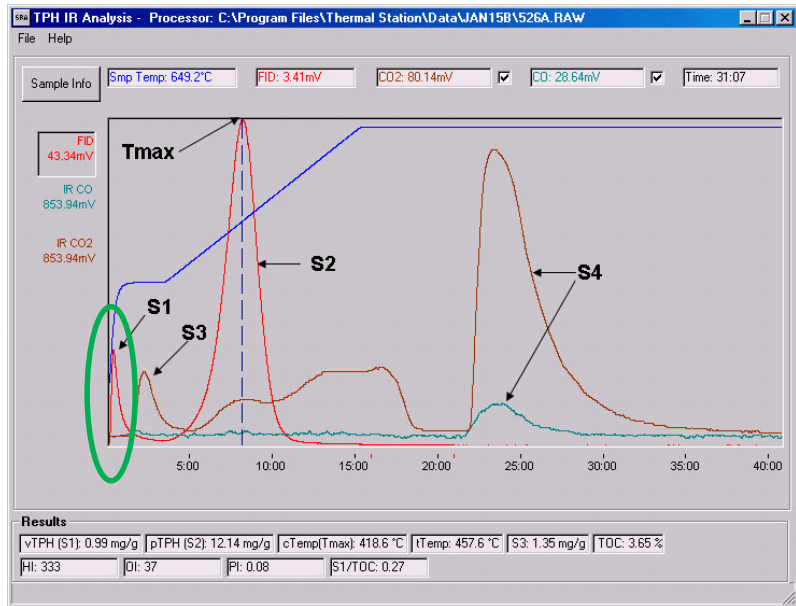


AAPG

Advancing the World of Petroleum Geosciences.

Programmed Pyrolysis Volumetrics

- S1 values are quantified – mg HC/g rock.
- Two reasonable assumptions can be made (or real values can be applied), unit conversions are made and then OIP values can be estimated.



$$\rho_{oil} = \frac{0.886 \text{ g}}{\text{cc}} \quad \rho_{rock} = \frac{2.5 \text{ g}}{\text{cc}}$$

$$\frac{\text{mg HC}}{\text{g Rock}} = \frac{\frac{1 \times 10^{-3} \text{ g HC}}{0.886 \text{ g oil}}}{\frac{2.5 \text{ g shale}}{\text{cc}}} = \frac{1.13 \times 10^{-3} \text{ cc oil}}{0.4 \text{ cc shale}} = 2.82 \times 10^{-3} \frac{\text{cc oil}}{\text{cc shale}}$$

$$2.82 \times 10^{-3} \frac{\text{cc oil}}{\text{cc shale}} \left(\frac{6.29 \times 10^{-6} \frac{\text{bbl}}{\text{cc}}}{8.11 \times 10^{-10} \frac{\text{acre-ft}}{\text{cc}}} \right) = 21.89 \frac{\text{bbl}}{\text{acre-ft}}$$

$$S1 \times 21.89 = \frac{\text{bbl}}{\text{acre-ft}}$$

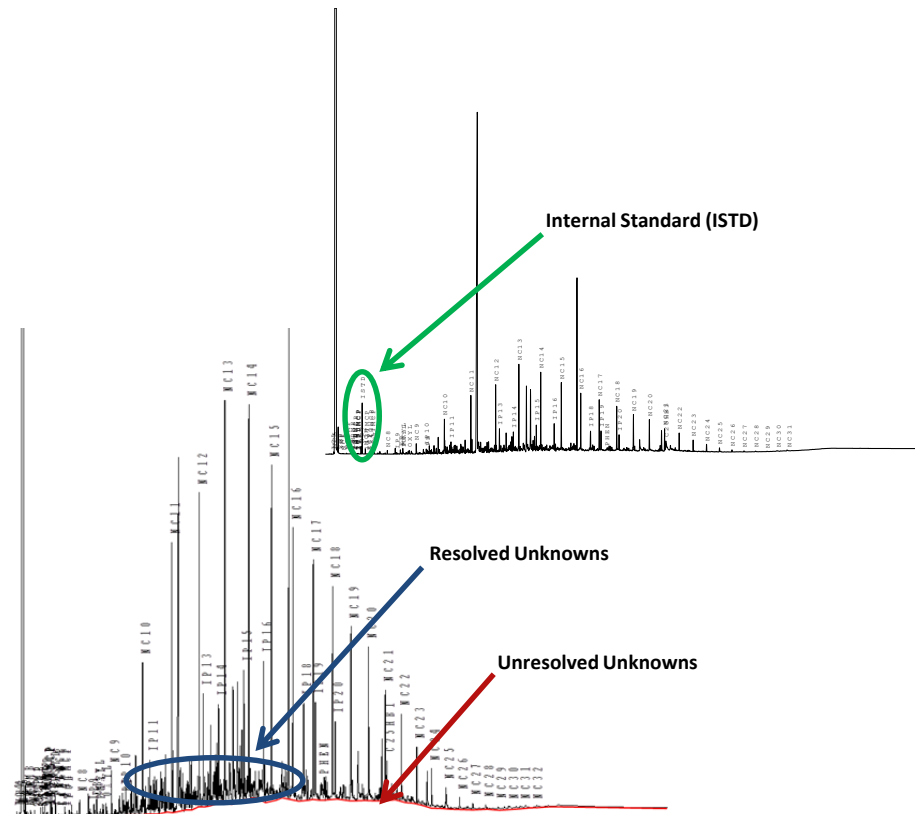


AAPG

Advancing the World of Petroleum Geosciences.

Cold Solvent – HRGC Volumetrics

- **Composite RSWC pressure core sample**
 - Sample aliquot is frozen and then crushed.
- **Tool annular fluids and baseline mud sample**
 - Fluids are centrifuged at 4000 rpm for 24 hrs.
 - Liquid phase is decanted into a separatory funnel and the FC-40, aqueous, and oil* phases are isolated from one another.
 - Solids are air dried and grain density is determined.
- **Composite RSWC pressure core sample, all annular fluid and baseline mud components**
 - The sample material is taken through a series of unheated extractions using cold CS₂ and the resulting extract is spiked with an internal standard (trans-2-heptene).
 - The extract is then subject to high resolution gas chromatography using the same standard conditions applied for whole oil/extracts.



*A real, free floating, measurable oil phase has yet to be observed.



AAPG

Advancing the World of Petroleum Geosciences.

Cold Solvent – HRGC Volumetrics

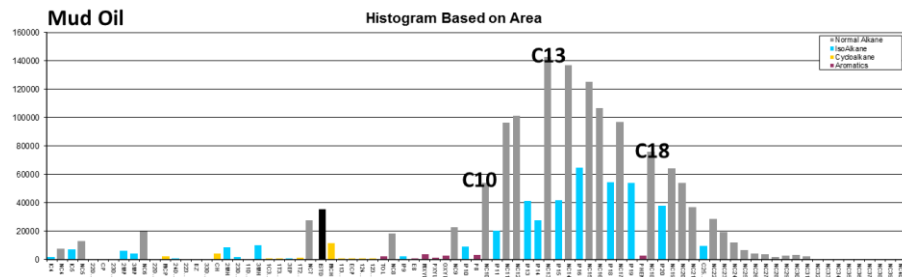
$$C = \frac{m_{ISTD}}{A_{ISTD}} \rightarrow m_{Oe}^i = A_T^i C$$

$$V_{Ot}^i = \frac{m_{Ot}^i}{\rho_o} \leftarrow m_{Ot}^i = \frac{m_{Oe}^i}{m_e^i} m_t^i$$

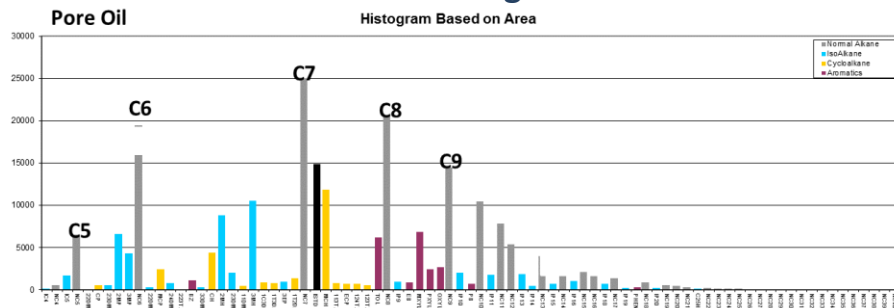
C quantitative conversion constant, g ISTD/ISTD integrated peak area
 m_{ISTD} mass of internal standard, g
 A_{ISTD} integrated area of the internal standard peak, unitless
 m_{Oe}^i mass of oil in the i^{th} component extract, g
 A_T^i total integrated area of all peaks in the i^{th} component extract, unitless
 m_{Ot}^i total mass of oil in the total mass of the i^{th} component, g
 m_e^i mass of the extracted i^{th} component aliquot, g
 m_t^i total mass of the i^{th} component, g
 V_{Ot}^i total volume of oil in the total mass of the i^{th} component, g
 ρ_o assumed oil density, g/cm³

i = RSWC composite sample, aqueous phase, or solid phase samples from tool annular fluids and baseline mud.

Diesel based OBM



Condensate from target reservoir





AAPG

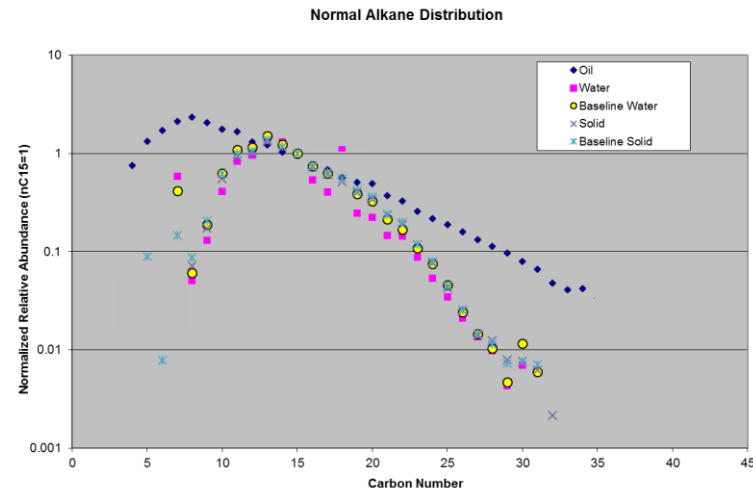
Advancing the World of Petroleum Geosciences.

Cold Solvent – HRGC Volumetrics

$$V_{OT} = V_{Ot}^c + V_{Ot}^a + V_{Ot}^s + V_{Of}$$

$$S_o = \frac{V_{OT}}{\left(\frac{m_t^c}{\rho_b} \right) \phi_t}$$

- Annular fluid oil character is compared to baseline mud oil character for QC/QA and deconvolution of pore fluids from those hydrocarbons sourced from drilling mud.



V_{OT}	total volume of oil identified as sourced from the RSWCs, cm^3
V_{Ot}^c	total volume of oil extracted from the total mass of the RSWCs, cm^3
V_{Ot}^a	corrected total volume of oil extracted from the total mass of the aqueous phase from the annular fluids in the tool, cm^3
V_{Ot}^s	corrected total volume of oil extracted from the total mass of the solid phase from the annular fluids in the tool, cm^3
V_{Of}	corrected total volume of free phase oil obtained from the annular fluids in the tool, cm^3
S_o	final oil/condensate saturation, pore vol frac
m_t^c	total sample mass of all RSWCs, g
ρ_b	CRA or retort bulk density determined from the composite RSWC sample, g/cm^3
ϕ_t	CRA or retort total porosity determined from the composite RSWC sample, bulk vol frac



AAPG

Advancing the World of Petroleum Geosciences.

Determination of Material Balance of Hydrocarbons – Caveats

- Our experience suggests there are permeability limits (no more than a few microdarcys) to the RSWC pressure core tool's utility.
 - Care should be taken to ensure a fit-to-purpose mud system is applied to avoid mud filtrate invasion or HC expulsion from the skin of the wellbore.
 - Imbibition is still a possible problem under some circumstances.
- Tracing the mud system is always recommended.
- When the target interval is expected to contain liquid phase hydrocarbons drilling with OBM should be avoided.
 - In both WBM and OBM systems knowledge of the mud “recipe” is important. Regardless, if mud additives are identical to in-situ pore components, it can be difficult (or impossible) to delineate what volumes are from the pore matrix and which are from the mud.
- If at all possible, produced fluids (water and oil) from an offset well should also be evaluated.
- Even after evaluating 90+ RSWC pressure core runs we have yet to actually observe a true, free oil phase when analyzing the annular fluids trapped in the tool.
 - For that matter, out of all the runs we have evaluated only a small fraction of them have shown to have exuded quantifiable volumes of pore fluids out of cores and into the annular packing fluid in the tool. The majority of the time the liquid phase hydrocarbons characterized in the annular fluid components can be readily traced back to being sourced from trapped drilling mud.



AAPG

Advancing the World of Petroleum Geosciences.

Final Material Balance of Hydrocarbons – Gas

- If a post-mature gas play then:

$$G_t = G_f + G_a$$

$$G_f = 32.0368 \frac{\phi_t S_g - \phi_a}{\rho_b B_g}$$

$$B_g = \left[\frac{p_{sc}}{z_{sc} (T_{sc} + 459.67)} \right] \left[\frac{z (T_r + 459.67)}{p_r} \right]$$

- In a gas play the total material balance of hydrocarbons is completed subsequent to crushed gas analysis.
- If we are confident the measured gas volumes are reliable, and the adsorbed-gas corrected ϕS_g is well established, we can back calculate an accurate reservoir pressure (assuming reservoir temperature is known).

G_t	total RSWC pressure core tool gas content, scf/ton
V_g	gas volume measured from the tool, cm ³
m_t^c	total sample mass of all RSWCs, g
G_c	crushed gas content, scf/ton
G_f	free gas volume, scf/ton
G_a	adsorbed gas volume, scf/ton
ϕ_t	CRA or retort total porosity, fraction of bulk volume
S_g	CRA or retort gas saturation, fraction of porosity
ϕ_a	Adsorbed gas filled porosity, fraction of bulk volume
ρ_b	CRA or Retort bulk density, g/cm ³
B_g	formation volume factor, res. vol./surf. vol.
p	pressure, psia
T	temperature, °F
z	real gas deviation factor, dimensionless
sc	standard conditions
r	reservoir conditions



AAPG

Advancing the World of Petroleum Geosciences.

Final Material Balance of Hydrocarbons – Oil

Example Only. Based on observed trends but not real data.

Method*	Attributes	OIP	NOC
		bbl/acre-ft	
Pyrolysis	300° Thermal extraction, mass/mass basis converted to volume/volume basis	96.41	103
Retort	300° thermal extraction, volume/volume basis (and mass/mass basis)	114.73	122.57
Cold Solvent Extraction - HRGC	Cold CS ₂ solvent extraction, mass/mass basis converted to volume/volume basis	160.62	171.6
CRA	Toluene reflux solvent extraction, mass difference converted to volume/volume basis	191.6	204.69

$$NOC = \frac{S1}{TOC} 100$$

NOC normalized oil content, mg HC/g TOC

S1 pyrolysis S1 peak, mg HC/g Rock

TOC total organic carbon, wt. %

*Final OIP for all methods includes the oil volumes determined from CS₂ extraction of the annular fluids entrained within the pressure core tool.

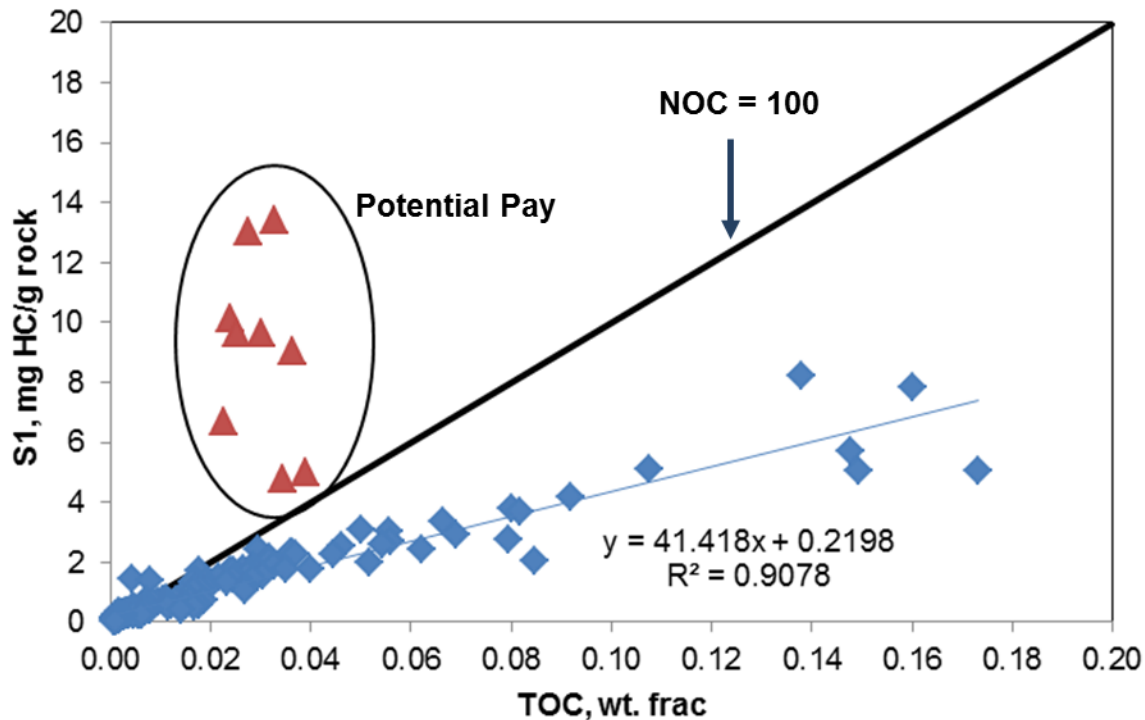


AAPG

Advancing the World of Petroleum Geosciences.

Importance of Prolific Oil Saturation on OIP Producibility

- When $\text{NOC} > 100$, whenever tested, always flowed oil/gas.
- When $\text{NOC} < 100$, variable results but usually negative.
- **Most economic unconventional oil plays have oil saturations greater than 100 mg of oil per gram of TOC and contain over 1 mg HC/g Rock.**



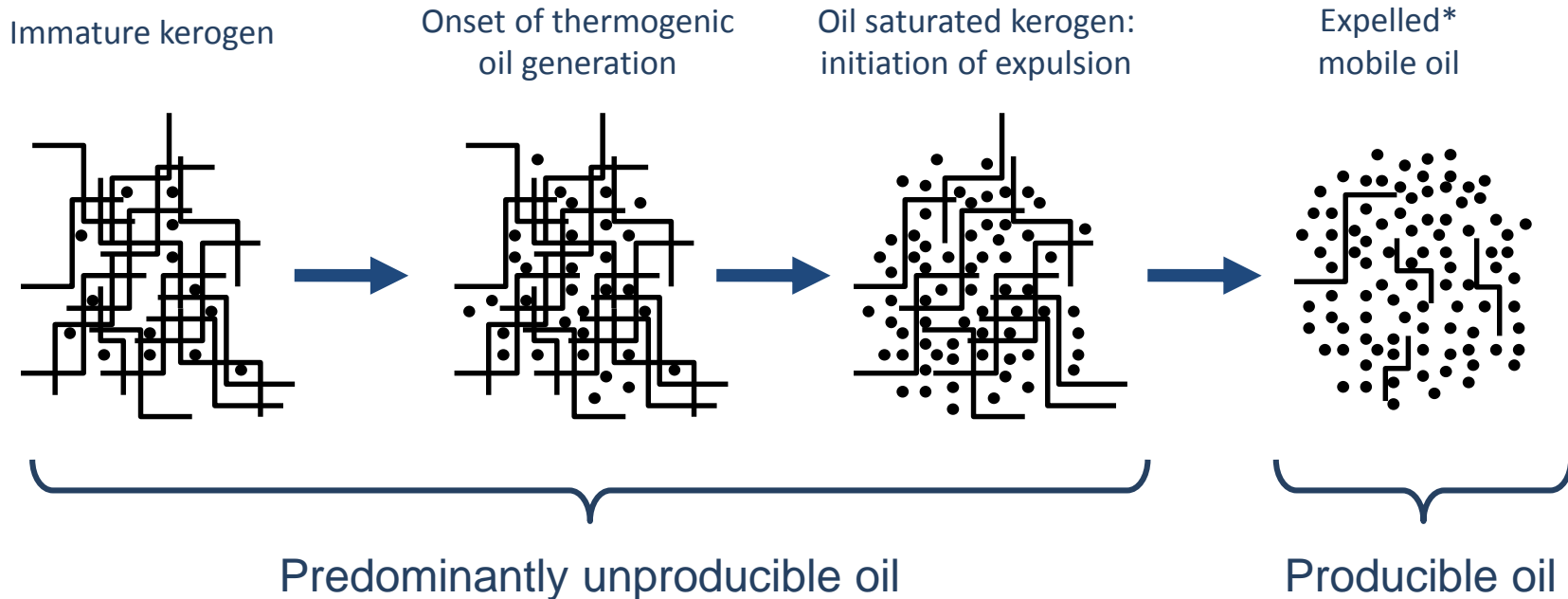
Modified from Ruble, 2010, and Jarvie, 2010



AAPG

Advancing the World of Petroleum Geosciences.

Unconventional Reservoir Measured OIP Caveats



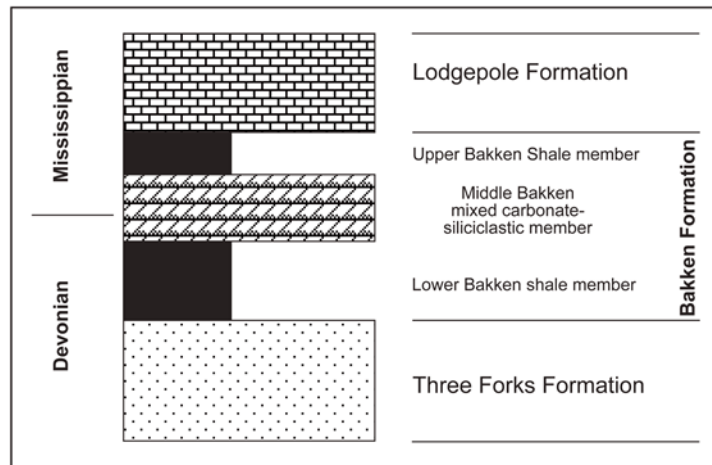
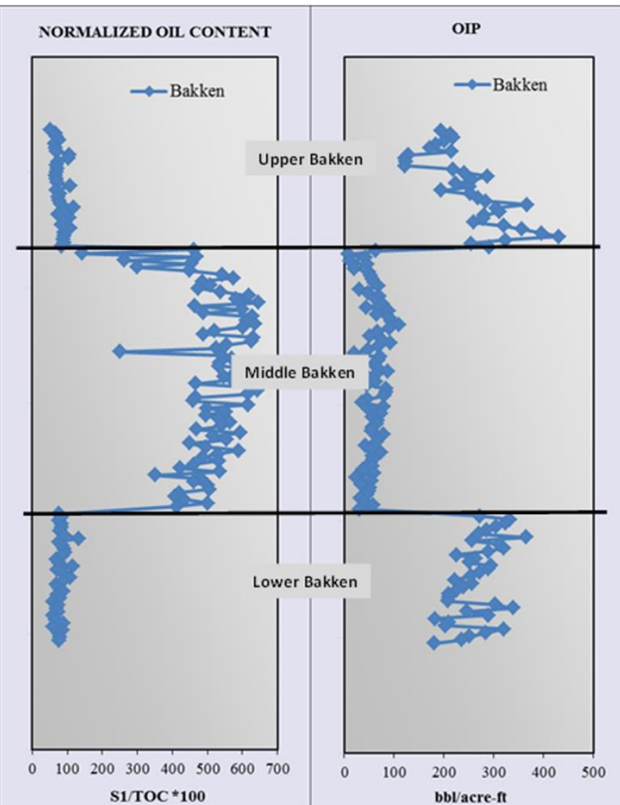
**Expulsion here refers to expulsion from kerogen and does not necessarily suggest primary expulsion and migration from the source rock.*



AAPG

Advancing the World of Petroleum Geosciences.

Importance of Prolific Oil Saturation on OIP Producibility

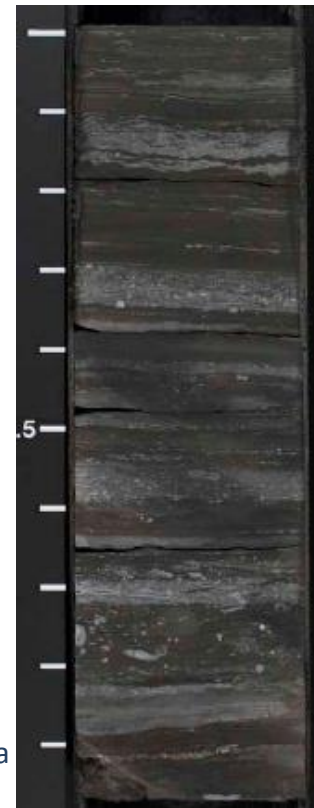


Egenhoff et al, 2010

Flagged Pay

- NOC > 100
- Oil > 1 mg Oil/g Rock
- ϕS_o (frac BV) > 0.01

- 1 ft core interval.
- Carbonate lithology.
- Contains the same laminated facies on a much smaller scale.





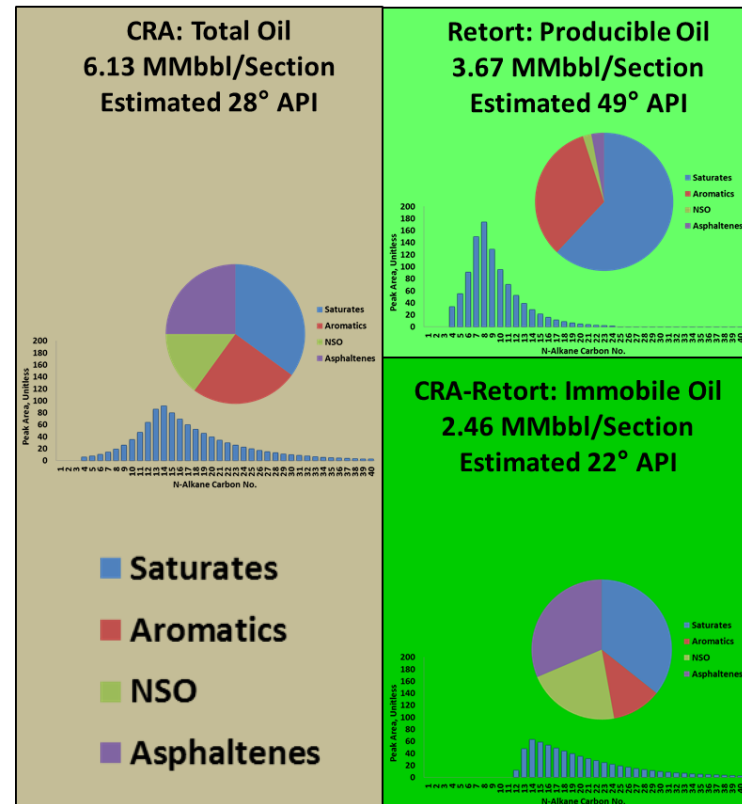
AAPG

Advancing the World of Petroleum Geosciences.

Characterization of OIP Volumetrics – Implications of Total vs. Producing OIP

- The produced oil from the Bakken, Eagleford, and Niobrara ranges from 35° and 60° API gravity. Molecular weight can be estimated from API gravity after Lasater, 1958*. The apparent range of oil gravity suggests the molar mass of the oils produced from these plays are approximately 100-200 lbmols.
- If we very simplistically assume these produced oils are composed of normal alkanes (C_nH_{2n+2}) then they would contain hydrocarbons ranging from approximately C_7 to C_{15} .
- Considering the programmed pyrolysis S1 peak and the hydrocarbon distillates from retort are the result of the volatilization of hydrocarbons at an isothermal temperature of 300°C it is quite reasonable to consider that these two thermal methods provide a better measure of **producing** OIP (B.P. of $C_{17}H_{36}$ = 302°C).
- By evaluating the oil compositional character we can better understand OIP volumetrics in terms of reservoir quality and economic producibility.

$$* MW = \left(\frac{7864.9}{API^\circ} \right)^{1.0386}$$



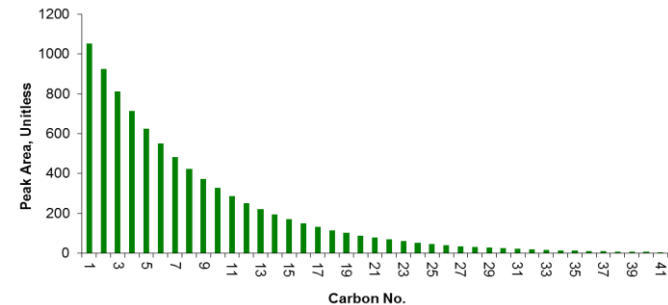
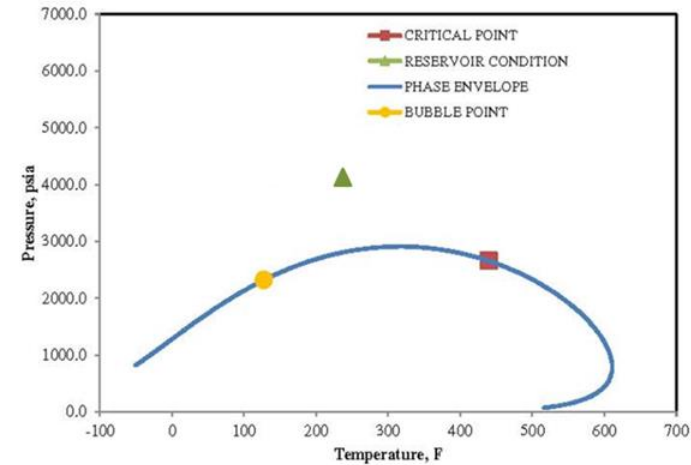


AAPG

Advancing the World of Petroleum Geosciences.

Final Material Balance of Total Hydrocarbons

- In a post-mature gas play total material balance of hydrocarbons is the total gas content determined subsequent to crushed gas analysis.
- In a bubble point system the computed total oil volumes represent OIP. The associated measured gas volumes enable determination of GOR estimates. The GOR values here are consistently lower than production GORs due to our ability to ascertain complete material balance (i.e. RF = 100%).
- In a dew point system the computed total oil volumes represent condensate volumes per unit volume of reservoir. The associated gas volumes enable determination of CGR estimates. The CGR values here are consistently higher than production CGRs due to our ability to ascertain complete material balance (i.e. RF = 100%).
- Because we effectively obtain a volumetrically quantified profile of hydrocarbons from C1 to C40+ we can use these data, accurate estimates of reservoir P & T, and equation-of-state (EOS) modeling software, to obtain estimates of fluid phase behavior. This allows for first pass PVT evaluation prior to well completions and any subsequent production.





AAPG

Advancing the World of Petroleum Geosciences.

Thank You Very Much!

Questions?