

SHALE GAS LOG EVALUATION FOR GAS VOLUME CALCULATIONS

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Keywords: Unconventional petrophysics, Shale gas reservoirs, log evaluation, gas volume calculations.

Abstract

The log analysis of shale gas resource are more complicated than conventional reservoirs. The shale gas plays are source rocks characterized by complex pore systems low to moderate multiple porosity and ultra-low permeability. The in-situ pore volume to take account both free gas and adsorbed gas. The kerogen includes organic carbon. The shale gas reservoirs show remarkable variation in lithology from clay-stone to marl-stone, mud-stone to sandstone and carbonate. Log analysis of unconventional reservoirs calls for core support for evaluating organic content (TOC) and guide to silly results, if conventional methods used for log interpretation. Validation of mineral model is achieved through direct comparison of the resulting elemental composition with XRD and XRF and may adjusting mineral end-points in lithology model. The NMR primarily benefits inorganic porosity and estimates more valid effective free porosity than neutron density. Generally calculated free gas porosity from neutron density is higher than NMR porosity, so a cross plot of n_{mr_phi} versus Φ_{nd} is a good test for calibration of Φ_{nd} . The total carbon content calculates from "Rock-Eval. Pyrolysis Analysis" and vitrinite reflectance measure kerogen weight%, kerogen type identification, kerogen maturity and adsorbed gas content. The conventional logs (density, sonic, GR, resistivity) are used for up-scaling measured parameters. The clay volume is calculated from spectral gamma ray (NGS). The calculated total porosity should be corrected to shale and kerogen effects and determined effective

porosity. The "Simandoux" equation is preferred to use for determining water saturation. The simultaneous equation solutions are widely used in multi-mineral evaluation for mineral and fluids volumes determinations. The TOC and sand volume fractions are key requirements for definition of cutoff criteria. The total in-placed gas volume comes from contribution of adsorbed gas at the surface of kerogen and free gas found in the kerogen pores. The suite of logs plus additional modern logs; ECS, NMR, FMI, DSI are needed for valid log evaluation.

1. Introduction

Essentially there is decline in the world conventional oil reservoirs production. Shale gas reservoirs are an extensive gas resources, however they require additional technology to enable them to be produced. The conventional resources, which correspond to light crude oil and sweet natural gas trapped into porous and permeable reservoirs. These resources can be produced at a relatively low cost because hydrocarbons flow out of the reservoir by natural depletion and no expensive upgrading processing is required. But when the reservoir or the fluid properties, or both deteriorate, it becomes necessary to apply specific technologies to extract and/or upgrade these resources. The application of these technologies comes at an increasing financial and environmental risk, which makes unconventional resources more challenging for development. The unconventional reservoirs worldwide are large volume but hard to develop. The organic-rich rocks are usually composed of three components, rock matrix, solid organic matter and the fluid(s) filling the pore space, while non-source rocks are composed primarily of only two components, the rock matrix and the fluid filling the pore space.

2. Methodology, Processing, Mathematics and Equations:

2.1 TOC Characterization from Logs

The Kerogen Weight Fraction from Passay and Shmoker/Hester Methods are used for TOC analysis from logs.

2.1.1 Passays Method:

The deep resistivity log and a porosity log (density or sonic) are used in this method and it is called "DlogR". The separation between resistivity and porosity logs show shale gas play.

$$\text{SlogR} = \log(\text{RESD} / \text{RESDbase}) + 0.02 * (\text{DTC} - \text{DTCbase})$$

$$\text{Wtoc} = \text{SF1s} * (\text{SlogR} * 10^{(0.297 - 0.1688 * \text{LOM})}) + \text{SO1s}$$

OR

$$\text{DlogR} = \log(\text{RESD} / \text{RESDbase}) - 2.5 * (\text{DENS} - \text{DENSbase})$$

$$\text{Wtoc} = \text{SF1d} * (\text{DlogR} * 10^{(0.297 - 0.1688 * \text{LOM})}) + \text{SO1d}$$

Where,

RESDbase, DTCbase and DENSbase: baseline log reading in non-source rock in the shale

SlogR or DlogR or NlogR: Passey's number from sonic or density or neutron log (fractional)

LOM: level of organic maturity (unitless) from vitrinite reflectance

Wtoc: total organic carbon from Passey's method (weight fraction)

SF1s,d,n and SO1s,d,n: scale factor and scale offset to calibrate to lab values of TOC

The constants in the Passey equations require DTC values in usec/ft and density in g/cc.

The results should be calibrated with measured geochemical laboratory TOC weight%.

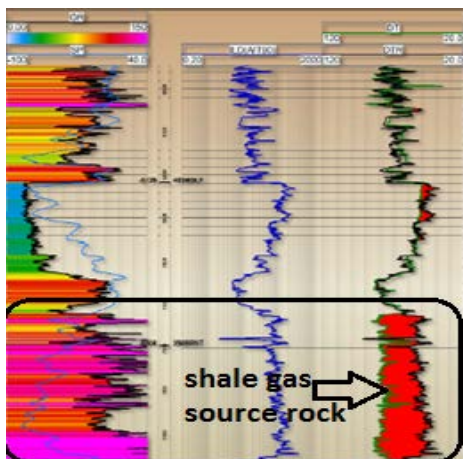


Figure 1. Passay's DlogR Plot

2.1.2 Shmoker/Hester Method:

$$\text{TOC (wt\%)} = (154.497/\text{Rho}_b) - 57.261$$

Where,

TOC: total organic carbon weight%

Rho_b: formation density as measured by density log

Depth m	TOC wt%	S1	S2	S3	Tmax °C	Ro %	SI	OI
X025	1.35	0.05	1.72	0.63	444		128	47
X040	1.18	0.05	1.65	0.57	443		140	49
X050	0.83	0.03	1.31	0.55	443		158	66
X065	0.8	0.04	1	0.58	440		126	73
X075	0.75	0.05	1.04	0.72	438		138	96
X090	1.04	0.09	2.52	0.29	452		241	28
X110	1.02	0.05	1.16	0.56	441		114	55
X135	1.05	0.05	1.32	0.57	443		125	54

Table 1. Geochemical lab data with TOC weight % values

2.1.3 TOC Correlations:

- TOC is increased while density and Pe logs are decreased.
- TOC is increased while resistivity increased.
- TOC is increased while uranium increased.

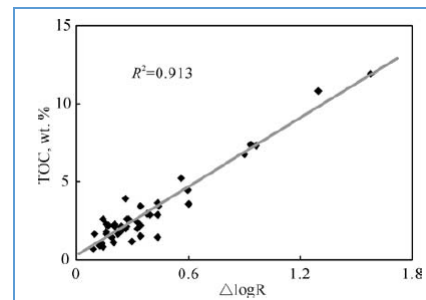


Figure 2. Correlation of core measured TOC and DlogR TOC

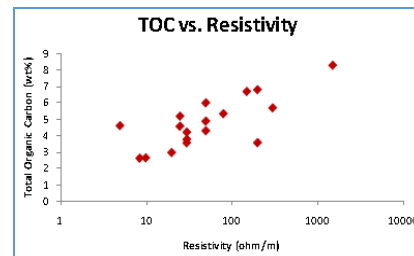


Figure 3. Correlation of core measured TOC and resistivity log

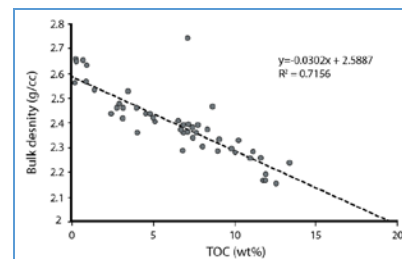


Figure 4. Correlation of core measured TOC and density log

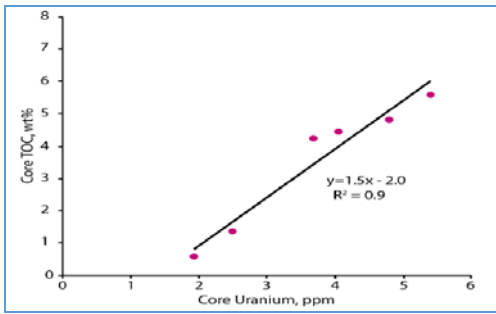


Figure 5. Correlation of core measured uranium

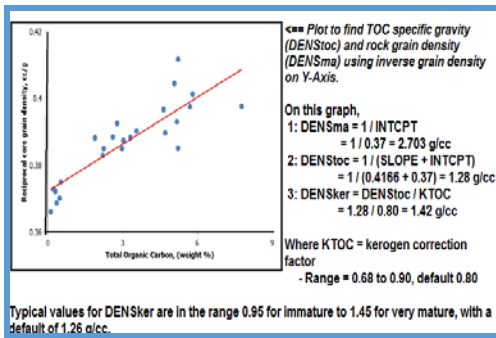


Figure 6. Kerogen density determinations

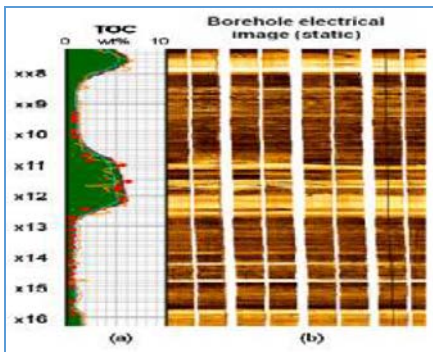


Figure 7. Confirmation of TOC by FMI image log

2.1.4 Analyzing TOC in the laboratory

The total organic carbon content of rocks is obtained by heating the rock in a furnace and combusting the organic matter to carbon dioxide. The amount of carbon dioxide liberated is proportional to the amount of carbon liberated in the furnace, which in turn is related to the carbon content of the rock. The carbon dioxide liberated can be measured several different ways. The most common methods use a thermal conductivity detector or infrared spectroscopy. Many source rocks also include inorganic sources of carbon such as carbonates and most notably calcite, dolomite, and siderite. These minerals break down at high temperature, generating carbon dioxide and thus their presence must be corrected in order to determine the organic carbon content. Generally, the amount of carbonate is determined by acid digestion (normally 50% HCl) and the carbon dioxide generated is measured and then subtracted from the total carbon dioxide to obtain the

organic fraction. Total organic carbon is often taken to mean the same thing as kerogen, but this is not the case. Kerogen is made up of oxygen, nitrogen, sulphur, and hydrogen, in addition to carbon. The standard pyrolysis lab procedure measures only the carbon, so total organic carbon excludes the other elements. About 80% of a typical kerogen (by weight) is carbon, so the weight fraction of TOC is 80% of the kerogen weight. The factor is lower for less mature and higher for more mature kerogen:

Kerogen volume is calculated by converting TOC weight fraction (Wtoc). The lab TOC value is a measure of only the carbon content in the kerogen. The kerogen also contains oxygen, nitrogen, sulphur, etc, so conversion of TOC into kerogen has to take this into account. The kerogen conversion factor (KTOC) is the ratio of carbon weight to the total kerogen weight. The factor can range from 0.68 to 0.95, with the most common value near 0.80. Converting mass fraction to volume fraction are follows: $W_{toc} = TOC\% / 100$ from core

or

$$W_{ker} = W_{toc} / KTOC$$

$$VOL_{ker} = W_{ker} / DENS_{ker}$$

$$VOL_{ma} = (1 - W_{ker}) / DENS_{ma}$$

$$VOL_{rock} = VOL_{ker} + VOL_{ma}$$

$$V_{ker} = VOL_{ker} / VOL_{rock}$$

Where,

KTOC: kerogen conversion factor Range = 0.68 to 0.95, default = 0.80

Wker: mass fraction of kerogen (unitless)

DENSker: density of kerogen (Kg/m³ or g/cc)

DENSma: matrix density (Kg/m³ or g/cc)

VOLxx: component volumes (m³ or cc)

Vker: volume fraction of kerogen (unitless)

DENSker is in the range of 1200 to 1400 Kg/m³, similar to good quality coal. Default = 1300 Kg/m³.

2.1.5 Deterministic and Multimin Solutions for Log Evaluation

Deterministic Solution

The deterministic method follows below steps for log evaluation of free porosity and fluids.

Shale volume

Shale volume calculations from a uranium corrected gamma ray curve (CGR) is the best.

$$VSH_{cgr} = (CGR - CGR_0) / (CGR_{100} - CGR_0)$$

When CGR is not available, we fall back to the thorium (TH) curve from a spectral gamma ray log

$$VSH_{th} = (TH - TH_0) / (TH_{100} - TH_0)$$

When TH are missing, the total gamma ray curve (GR) can still be used by moving the clean (GR₀) and shale (GR₁₀₀) lines further to the right compared to conventional shaly sands.

$$VSH_{gr} = (GR - GR_0) / (GR_{100} - GR_0)$$

The calculated clay volume should be calibrate with XRD clay volume weight%.

Kerogen and Shale corrected Porosity

Effective porosity is best done with the shale corrected density neutron complex lithology model, also modified to correct for kerogen volume.

$PHID_{ker} = (2650 - DENS_{ker}) / 1650$ (if PHIN is in Sandstone Units)

$PHIDc = PHID - (V_{sh} * PHID_{sh}) - (V_{ker} * PHID_{ker})$

$PHInc = PHIN - (V_{sh} * PHIN_{sh}) - (V_{ker} * PHIN_{ker})$

$PHIe = (PHInc + PHIDc) / 2$

PHIN_{ker} is in the range of 0.45 to 0.75, similar to poor quality coal. Default = 0.65.

If density log do not available or is affected by rough borehole, the shale corrected sonic log porosity (PHIS) can be used instead:

$PHIS_{ker} = (DTCK_{ker} - 182) / 474$ (if PHIN is in Sandstone Unit)

$PHISc = PHIS - (V_{sh} * PHIS_{sh}) - (V_{ker} * PHIS_{ker})$

$PHInc = PHIN - (V_{sh} * PHIN_{sh}) - (V_{ker} * PHIN_{ker})$

$PHIe = (PHInc + PHISc) / 2$

DTCK_{ker} is in the range of 345 to 525 usec/m, similar to good quality coal. Default = 425 usec/m.

Effective porosity from a nuclear magnetic resonance (NMR) log does not include kerogen or clay bound water, so this curve, where available is a good test of the modified density neutron cross plot method.

In all cases, good core control is essential. If porosity is too low compared to the core porosity, then shale volume or kerogen volume are too high and should be rechecked.

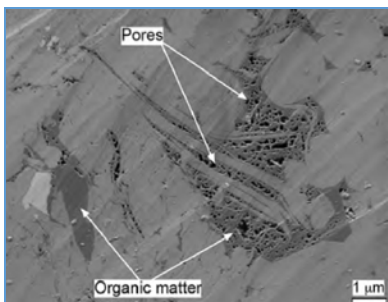


Figure 8. Kerogen free porosity and organic matter

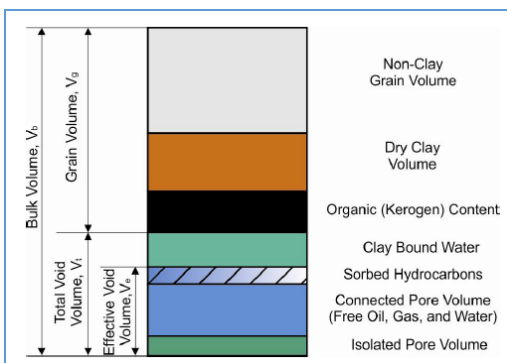


Figure 9. Shale gas porosity model

Kerogen Porosity Estimation

The kerogen porosity is calculated from NMR porosity and neutron density porosity

$$\text{Phi (kerogen)} = \text{Phi (ND)} - \text{Phi (nmr)}$$

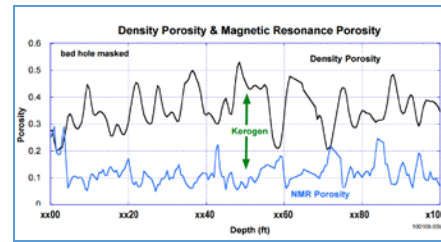


Figure 10. Kerogen porosity

Lithology

Lithology is calculated with a kerogen and shale corrected 3-mineral model using kerogen-and shale corrected Pe, density, and neutron logs and results is calibrate o XRD data. To achieve a reasonable match the mineral end points should be modified.

Water Saturation

Water saturation is best done with the Simandoux equation, which is better behaved in low porosity than most other models.

$$\frac{1}{R_t} = \frac{\phi^m \times S_w^n}{a \times R_w} + \frac{V_{cl} \times S_w}{R_{cl}}$$

Where,

R_t: true resistivity (ohm,m)

m: cementation Exponent (unitless)

n: saturation exponent (unitless)

S_w: water saturation (fractional)

V_{cl}: cly volume (fractional)

R_{cl}: clay resistivity (ohm.m)

R_w: formation water resistivity (ohm.m)

A: tortiosity factor (unitless)

Phi: porosity (fractional)

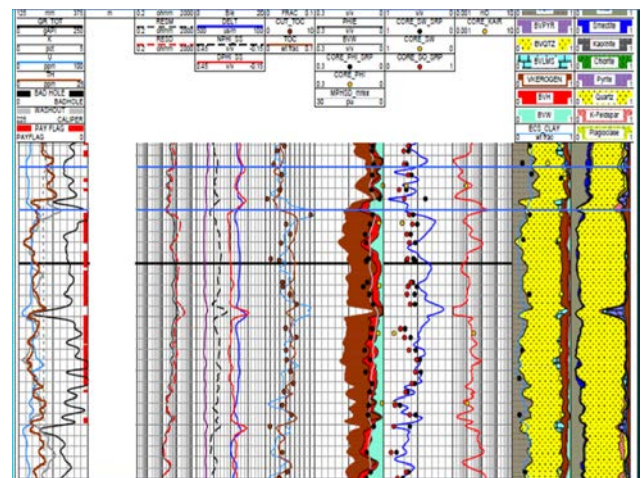


Figure 11. Log interpretation of a shale gas formation

Permeability

An alternative is the exponential equation derived from regression of core permeability against core porosity. The equation takes the form of ; Perm = 10 ^ (A1 * PHIE + A2). Typical values for A1 and A2 are 20.0 and -3.0 respectively. This model will match conventional core permeability quite well, but will probably not match the permeability derived from crushed samples based on American Research Institute (GRI) protocol. High perm data points caused by micro or macro fractures should be eliminated before performing the regression.

Cutoff

The key requirements for definition of cut-off parameters are:

- Sand volume fraction
- Brittleness
- Porosity
- TOC
- Net pay

Total Gas In-place

The total gas in-place for a shale gas reservoir:

Total GIP = Free GIP + Adsorbed GIP

- **Free Gas In-place**

Free gas in place is calculated from the usual volumetric equation:

$$GIP_{free} = KV4 * PHIE * (1 - Sw) * THICK * AREA / Bg$$
$$Bg = (Ps * (Tf + KT2)) / (Pf * (Ts + KT2)) * ZF$$

Where,

Bg = gas formation volume factor (fractional)

Pf = formation pressure (psi)

Ps = surface pressure (psi)

Tf = formation temperature (°F)

Ts = surface temperature (°F)

ZF = gas compressibility factor (fractional)

KT2 = 460°F

KV3 = 7758

KV4 = 0.000 043 560

- **Adsorbed Gas In-place**

Gas content from a best fit line versus TOC can be applied to log derived TOC:

Gc = KG11 * TOC%

Where,

Gc = gas content (scf/ton)

TOC% = total organic carbon (percent)

KG11 = gas conversion factor range = 5 to 15, default = 9

Adsorbed gas in place is derived from:

GIP_{adsorb} = KG6 * Gc * DENS * THICK * AREA

DENS = layer density from log or lab measurement (g/cc)

KG6 = 1.3597*10⁻⁶

3. Shale Gas Core Analysis

3.1 Sample Preparation

300 g of sample is removed from preserved core by longitudinal slice with a band saw using nitrogen as lubricant. Each sample is weighed and bulk volume is measured by mercury immersion. These initial measurements are used to determine sample bulk density. At the second stage the sample (300 g) is crushed and sieved through 20 and 35 US mesh screens. The material retained on the 35 mesh screen, 100 g is used for Dean Stark and 50 g for permeability. The permeability measurement values have uncertainty, because the sample is crushed.

3.2 Core Objectives

- On-Site gas content and gas composition determination
- Total Organic Carbon analysis from Rock Eval-Pyrolysis
- Vitrinite Reflectance (Kerogen types and level of thermal maturity)
- Permeability, Porosity and Fluid Saturations
- Adsorbed gas content (Langmuir method)
- Rock mechanical properties
- Acoustic properties
- Core gamma (Spectral Gamma Recommended)
- Thin section description
- Petrography, scanning Electron Microscopy (SEM)
- XRD and XRF analysis

3.3 Rock-Eval Pyrolysis Analysis

Rock-Eval is a method of pyrolysis in an open environment and it is a direct measurement of TOC is accomplished at the well site and data is available within about 30 minutes of sample collection. During pyrolysis the sample is heated up to 600°C, while derived hydrocarbons. Heating distills free compounds (bitumen, S1) then cracked pyrolytic products from insoluble organic matter (kerogen, S2).

Source rock quality	Pyrolysis S ₂ , mg hydrocarbons/g rock
None	< 2
Poor	2 to 3
Fair	3 to 5
Good	5 to 10
Very Good	>10

Table 2. Shale gas rock quality classification based on S2 Pick

Product type	Hydrogen Index
Gas	50 to 200
Gas and OIL	200 to 300
OIL	>300

Table 3. Classification of oil and gas based on hydrogen index

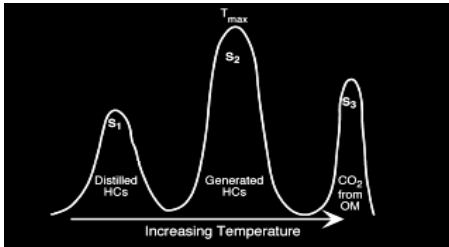


Figure 12. Kerogen S2 pick from Rock-Eval Pyrolysis

3.4 Adsorbed Gas Content (Long Muir Isotherm method)

Adsorption isotherms indicate the maximum volume of methane that a gas shale can store under equilibrium conditions at a given pressure and temperature. The direct method of determining adsorption isotherm involves cutting core that is immediately placed in canisters, followed by measurements of the gas volume evolved from the shale over time. When the sample no longer evolves gas, it is crushed and the residual gas is measured (scf/ton).

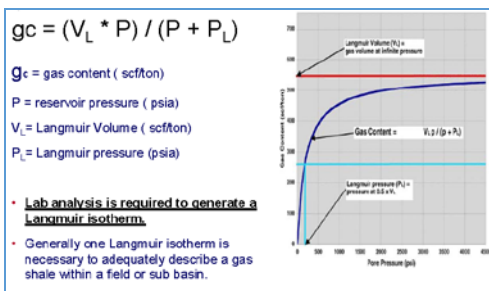


Figure 13. Longmuir isotherm (Gs)

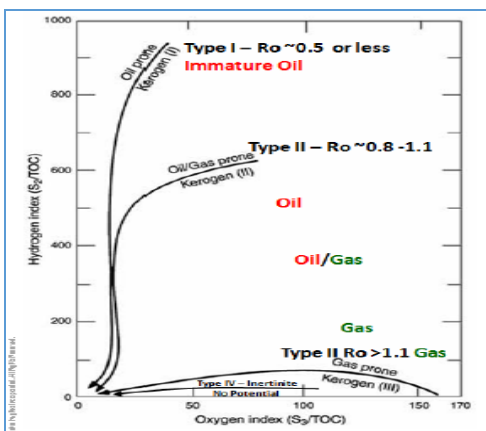


Figure 14. Kerogen types from vitrinite reflectance

3.5 Shale Gas Sweet Spot Identification

Sweet spots are defined as the most prospective volumes of the shale play. They are primarily targeted to achieve early economic production. The identification of sweet spots has been synthesized into recognizing zones of good hydrocarbon reservoir quality (TOC and thermal maturity, por-perm character, fluid saturations, gas in place) and good completion quality (stress regime, mineralogy, natural fractures). Thus, a sweet spot can be described as a formation volume that has the following characteristics:

- low water saturation with high TOC content and hence high kerogen content
- low clay content and hence high brittleness index for hydraulic fracture ability
- higher porosity
- inter particle permeability

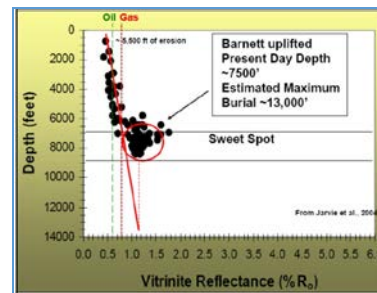


Figure 15. Sweet spot identification from depth vs vitrinite reflectance (R0)

3.6 Multiminerall Solution

The simultaneous equations solution are used for determination of mineralogy, porosity and fluids volumes. A petrophysical model is generated based on reservoir lithology and fluids. The mineral end points are calibrated to the core and XRD. The kerogen is included as a mineral to lithology model to estimate kerogen volume. The below lithogy model demonstrated for a carbonate formation.

MULTI-MINERAL MODEL

Simultaneous equation solutions are widely used in multi mineral evaluation from logs. A typical equation set for a gas shale would be:

$$DENS = 2.35 * V_{sh} + 2.65 * V_{qtz} + 2.71 * V_{lim} + 2.87 * V_{dol} + 1.15 * V_{ker} + 0.4 * PHle$$

$$DTC = 120 * V_{sh} + 55 * V_{qtz} + 47 * V_{lim} + 43 * V_{dol} + 200 * V_{ker} + 250 * PHle$$

$$PHIN = 0.30 * V_{sh} - 0.03 * V_{qtz} + 0.00 * V_{lim} + 0.04 * V_{dol} + 0.95 * V_{ker} + 0.70 * PHle$$

$$PE = 3.45 * V_{sh} + 1.85 * V_{qtz} + 5.10 * V_{lim} + 3.10 * V_{dol} + 0.95 * V_{ker} - 0.01 * PHle$$

$$1.00 = V_{sh} + V_{qtz} + V_{lim} + V_{dol} + V_{ker} + PHle$$

PHle and Vker could come from relationships between core data and one or more logs. The above mineral properties are in English units and will need some adjustment to suit local conditions and to prevent negative answers.

Where,
Vxxx = Volume of shale, quartz, limestone, dolostone, and kerogen.

Figure 16. Multi-mineral model for a carbonate formation

4 Conclusions

- Shale gas resources are unconventional reservoirs within low to moderate multiple porosity and ultra-low permeability.
- The organic matter is in the form of solid kerogen.
- The reservoir gas volume comes from both free gas and adsorbed gas volumes.
- The logs are used for up-scaling core measured parameters.
- The core samples are prepared based on GRI protocol.
- The Rock-Eval Pyrolysis is used for kerogen weight% measurement,
- The adsorbed gas content measured by Vitrinite analysis (Long Muir method).
- The DlogR and Schmoker/Hester methods are used for TOC determinations from logs.
- The clay volume is calculated from spectral GR and calibrated with XRD data.
- The effective porosity is calculated from neutron and density logs, kerogen and clay effects corrected. The neutron density porosity is calibrated with NMR porosity.
- The kerogen type identified by measured LOM. The kerogen type 3 is gas.
- The calculated lithology is calibrated with thin sections and petrography.
- Generally Simandoux equation calculates valid water saturation results.
- The measured S₂ (mg gas/ gr rock) by pyrolysis analysis is used for classification of the source rock quality.
- The total gas volume calculated from both free gas volume and adsorbed gas volume.

5 Acknowledgments

TOC: total carbon content

LOM: Kerogen thermal level of maturity

S₂: kerogen volume (mg gas/gr rock)

DlogR: Passay's method for TOC determination

RD: deep resistivity

R_{hob}: bulk density

CGR: corrected GR (TH, K)

GIP: free gas in-place

G_s: adsorbed gas content

B_g: gas formation volume factor

V_{cl}: clay volume

Phi: porosity

S_w: water saturation

GRI: American Gas Research Institute

XRD: X Ray Diffraction

PHISc: corrected sonic porosity

PHIDc: corrected density porosity

PHINc: corrected neutron porosity

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