An Integrated Petrophysical Approach for Shale Gas Reservoirs

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Shale Gas Formation – Geological Setting

- Organic-rich, fine-grained sedimentary rock
- Seal, source and reservoir
- Variable composition of clay, quartz, carbonates and other minerals
- Regionally extensive
- May also contain liquid hydrocarbon (shale oil)
Shale Gas Reservoir Evaluation Objectives

- Lithology and mineralogy
- Total organic content (TOC)
  - Kerogen type and maturity
- ‘Conventional’ petrophysical parameters
  - Porosity, permeability, gas saturation
- Total gas-in-place (GIIP)
  - Free gas and adsorbed gas in place per area
- Geologic characterization
  - Structural features and fractures
- Geomechanical reservoir characteristics
  - Stress regime and mechanical rock properties

- To optimize horizontal lateral well placement and effective stimulation and completion design
Petrophysical Data Sources

**Mineralogy Logs**
- Geochemistry
- Lithology
- Mineralogy
- Total organic content
- Lithofacies classification
- Total porosity
- Siliceous brittleness index

**Core (Cutting) Analysis**
- Source rock maturity
- Total organic content
- Mineralogy
- Bulk/Grain density
- Porosity and permeability
- Fluid saturation
- Mechanical properties
- De/Adsorption properties

**Microseismic**
- Induced hydraulic fracture characterization

**Resistivity, Density, Neutron**
- Total organic content
- Porosity and permeability
- Fluid saturation

**NMR**
- Porosity
- Permeability
- Fluid typing
- Total organic content

**Acoustic**
- Dynamic and static geomechanical properties
- Pressure gradient

**Image Logs**
- Structural and sedimentary analysis
- Stress regime
- Fracture characterization
Unconventional Shale Reservoir Petrophysical Evaluation: Lithology and Mineralogy

- **Why is quantifying mineralogy important?**
  - Reservoir quality in shales is largely dependent on the mineralogy
  - Variations in mineralogy indicate variations in the mechanical properties
  - One criterion in identification of lithofacies
  - Reduce uncertainty in the porosity calculation
  - TOC quantification

- **How is lithology/mineralogy determined?**
  - Conventional log responses
  - A variety of petrological and inorganic geochemistry core analyses
    - XRD, XRF, ICP-OES, ICP-MS, SEM – EDX, FIB-SEM, FTIR, TS, X-ray CT and micro CT imaging
  - Wireline elemental spectroscopy logging

Interpreted Mineralogies using the RockView™ expert system

Haynesville Shale  Barnett Shale  Eagle Ford Shale
Characterization of the total organic content (TOC) in shale reservoirs includes determination of:
- The amount of kerogen and its vertical distribution within the reservoir
- The kerogen type and the level of maturity

Calculation of the amount of TOC present can be made using:
- Conventional log responses
  - Passey Delta Log R methodology
  - Relationships of density, GR, uranium with TOC
- Core analyses
- Pulsed neutron elemental spectroscopy
- NMR logging (in combination with elemental spectroscopy)

The Baker Hughes FLeX™/ RockView service provides two measurements of the quantity and distribution of TOC.
- Direct determination of TOC from the elemental carbon measurement
- An additional determination of TOC using NMR total porosity, the measured bulk density and the RockView determined mineralogy
Shale Gas Reservoir Petrophysical Workflow Components:
Elemental Spectroscopy Logging Quantification of Elemental Carbon

- Elemental spectroscopy logging expert system
- Quantifies the weight fraction of carbon in the formation
- All elemental carbon needed for the non-organic minerals present is first allocated

\[ \text{TOC} = [C_{\text{Total}} - C_{\text{Calcite}} - C_{\text{Dolomite}} - C_{\text{Siderite}}] \]

- Using several factors (including the Th/U ratio and the uranium content) the remaining carbon is classified as either:
  - Coal
  - Kerogen
  - Bitumen or oil
Organic Matrix – Kerogen Quality and Maturity from TOC Assessment

- Good source rock
  - Organic richness (wt% total organic content ‘TOC’)
  - Current and past maturity level (vitrinite reflectance, Ro)
  - Fluid window - oil, gas or mixture

Source – Dan Jarvie, Worldwide Geochemistry - AAPG European region ICE, 17-19 October 2010, Kiev, Ukraine
Various researchers have confirmed that:
- A significant percentage of total porosity in shale gas reservoirs is within the organic material.
- The organic porosity increases with increasing kerogen maturity as the kerogen generates gas.

The NMR T₂ relaxation response for the organic material and its porosity fall in the CBW / BVI ranges
- Hydrocarbons in the organic pores overlap with bound water due to surface relaxation.

These observations require modification to the NMR rock conceptual model for shale reservoirs.
Unconventional Shale Petrophysical Evaluation: Free Gas Calculation

- An Archie equation methodology is commonly used:
  - The preferred approach is to calibrate the parameters used with core “as received” saturation data.
    - The total porosity must be TOC corrected. We recommend the NMR total porosity.
    - One estimate of Rw can be obtained from the total porosity and resistivity values in non-organic shale intervals.
    - Pickett plots are helpful in the empirical adjustment of m and n
  - The selection of the shale formation water resistivity is problematic as is the underlying assumption that shale behaves as an Archie reservoir. However, this approach has been successfully employed in many reservoirs.

[Graph showing Free Gas Saturations calculated from an Archie Approach in the Woodford Shale]

Modified from Jacobi et al presentation at 2009 SPE ATCE
Shale Gas Reservoir Evaluation:
Gas In Place Calculation

- Core analyses are used to investigate the adsorbed gas volumes in shale reservoirs.
  - Langmuir Adsorption isotherm analyses are used to calculate the adsorbed gas volumes
  - Desorption isotherms are used to estimate the total gas volumes, which include adsorbed and free gas.

Definition of terms for a Langmuir Isotherm

The TOC wt % is the parameter is best estimated from log and core data. To incorporate the estimate of the adsorbed gas volumes we want to derive a relationship between gas content and TOC.

Gas Storage Capacity vs. TOC weight fractions

3 Antrim wells

\[ y = 7.226x + 5.0394 \]

\[ R^2 = 0.8689 \]
Unconventional Shale Petrophysical Evaluation: Geological Characterization

- Borehole imaging Applications in shale gas plays:
  - Resolve complex structures
  - Characterize natural fracture network
  - In-Situ stress determination
  - Stratigraphic analysis
  - Input for planning stimulation and completion design and horizontal lateral placement

Interpretation of Borehole Images adds Value in Vertical and Horizontal Wellbores
Identification of geologic hazards or fractures away from the wellbore can provide valuable input into the horizontal lateral well placement and well stimulation or completion design.
Unconventional Shale Petrophysical Evaluation: Lateral Characterization

- Operators are beginning to acquire more data to characterize horizontal laterals.
- Improved well productivity from more-effective stimulation and completion performance.
- The most frequently used technology is LWD resistivity imaging.
- Additional services include advanced mud logging:
  - Elemental and mineral XRD, XRF and SEM analyses, RoqSCAN™ performed at the wellsite
  - Extended mass spectrometry analysis to quantify higher-mass organic species (C1-C10)
  - Rock Eval Pyrolysis
Summary - Unconventional Petrophysical Workflow

Core/Log Acquisition; Core/Log Correlation; Depth/Gross thickness of Shale Gas Reservoir

- TOC Evaluation
- Porosity Modelling
- Gas Saturation Evaluation
- Free Gas in Place

- Mineral Modelling
- Permeability Modelling
- Sorbed Gas Determination
- Total Gas in Place

- Fracture Analysis
- Geomechanical Modelling
- Completion and Stimulation Design

- Formation Pressure; Formation Temperature; Gas Properties
Conclusions

- Shale reservoirs present a range of issues for the petrophysicist to address.
- There is no single solution to understanding shale reservoirs.
- Utilize the full range of analytical data available: logs, core, cuttings.

Thank You