SPE 153681

Shale Exploration Methodology and Workflow

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This paper was prepared for presentation at the SPE Middle East Unconventional Gas Conference and Exhibition held in Abu Dhabi, UAE, 23–25 January 2012.

Abstract

Exploration for shales has become an integral part of many operators' processes in the North American shale boom. While leveraging public data in existing plays is a major advantage, when looking outside those existing areas, a comprehensive plan must be developed. The shale-exploration methodology is fundamentally different from conventional exploration, with different drivers and metrics.

Shale exploration requires an exploration program that includes a heavy data-acquisition element. Beyond the initial geological identification of the prospect, wells need to be drilled to evaluate the potential of the shale prospect. Extensive coring, open-hole logging and formation pressure testing are required to answer four basic questions: Does the shale have enough total organic content? Does the shale have the thermal maturity necessary? Does the shale have the stimulation potential? Does the sale have a simple structural environment conducive to horizontal drilling? Once these questions have a satisfactory answer, the key shale properties can be mapped using multiple sources with the goal of identifying core areas suitable for further horizontal well evaluation.

This paper describes the process and workflow for a data-acquisition program and demonstrates not only the benefits of acquiring specific data, but also highlights the uses of the data to aid the exploration decision process. Examples are given of the type data acquired, and the analytical workflow is discussed.

Introduction

The first step in exploring for productive organic mudstone reservoirs is basin screening. This is done using regional geological studies along with any existing information available from the area under examination. Typically, shales that caused problems during drilling for conventional targets are seen as potential systems for further investigation. Once a basin has been identified using the screening tools outlined below, exploratory wells need to be drilled to acquire hard data.

In the hunt for potential shale reservoirs, it is common practice to fall back on conventional exploration techniques that have been used for many years. Tried-and-true methods of evaluating potential conventional reservoirs are looked at first, as this is within the comfort zone of many exploration departments. This approach has proven to be a difficult one, as shales exhibit distinctive properties that are not easily captured by conventional techniques. Metrics used for evaluating conventional reservoirs do not hold for the majority of unconventional shale plays. An example of this would be using resistivity measurements to determine water saturation. In most shales, water is clay bound and irreducible, so deriving water saturation is unnecessary.

Passey et al., in their 2010 paper, give a description of shale gas reservoirs and the scope of measurements made to determine the geological and petrophysical characterization or these systems. Information required to determine the potential viability of a particular play includes total organic carbon (TOC), maturity level (vitrinite reflectance), mineralogy, thickness, and organic matter type. Total gas, free gas, and adsorbed gas are important characteristics, as is porosity. Porosity in particular is a complex measurement in organic mudstone systems.

While the above measurements are key to the viability of a potential shale play, experience has shown that geomechanics and the ability to successfully stimulate using hydraulic stimulation methods is of equal importance. Any exploration program needs to measure the propensity of the rock to fracture with sufficient complexity to generate enough surface area for sustainable production rates.

Another consideration in rank exploration is the availability of tools and equipment to perform some of the specialized tests and data-acquisition programs. This is an important consideration when determining what is necessary and what is a luxury in terms of data acquisition (Kundert and Mullen 2009).

The goal of the initial exploration program is to answer a simple question: Does the resource warrant elevating to the appraisal stage? What the initial exploration will not be able to answer is the question about whether the exploration target is going to be economically successful. With the stated goal of answering the first question, we shall examine methods and workflows to obtain the right answer as efficiently as possible.

Basin Screening Criteria

The initial screening criteria for any basin consist of three parts. First are the surface issues, second are the subsurface properties of the organic-rich shales, and third are the economic regimes. The screening-criteria chart is characterized in **Fig. 1**.

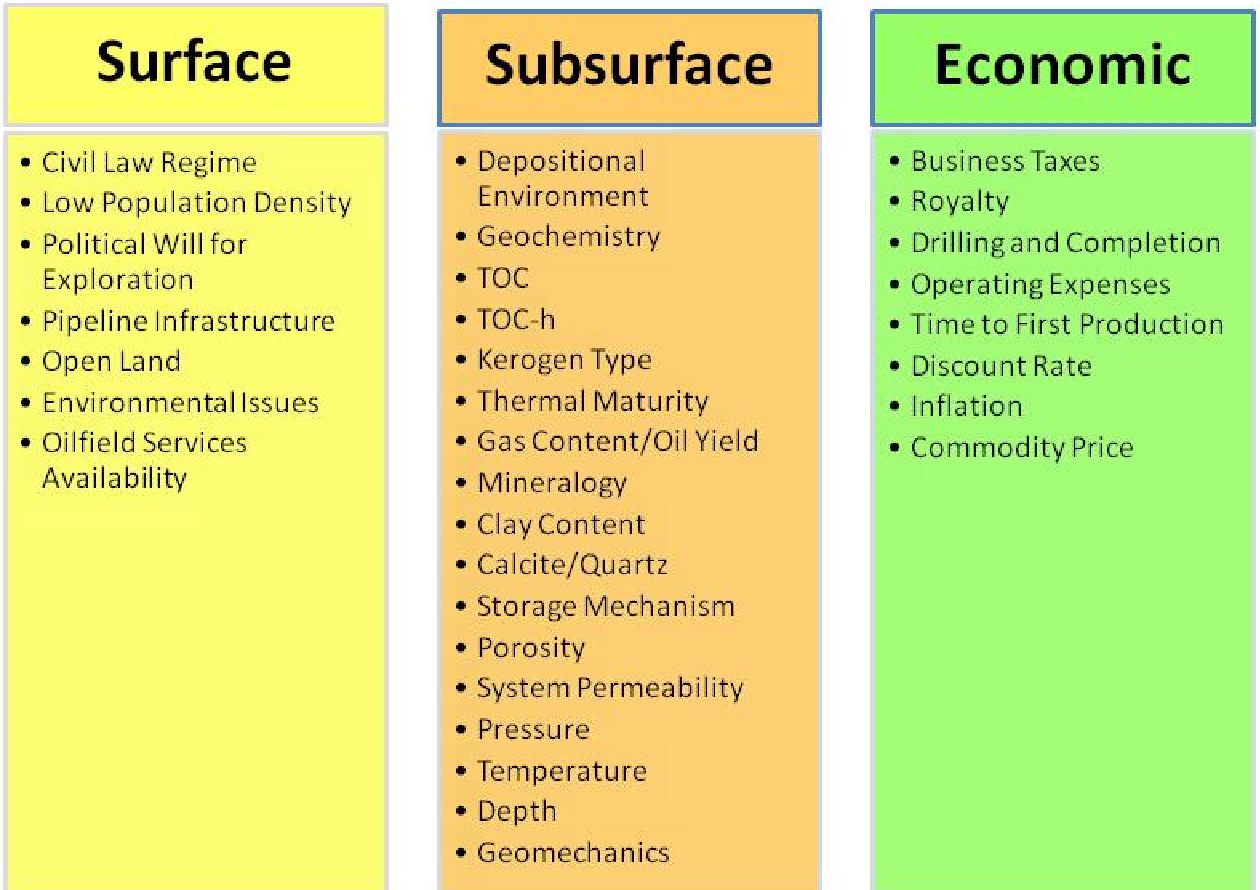


Fig. 1—Screening Criteria for Shale-Exploration Projects.

The way the screening process works is by constructing a list of countries to start looking with favorable metrics of the surface criteria and the economic criteria concerning taxes, royalty, and commodity price, as shown in Table 1. Most exploration ventures in new areas suffer a bit from the drilling and completion costs. A basin-focused literature survey for each sedimentary basin in each country is the next step in the process. Quite often, the best source of information about the hydrocarbon potential of the basin is from the geoscientists and basin modelers examining the hydrocarbon systems in these basins looking for the hydrocarbon sourcing for conventional reservoir traps. There is a wealth of knowledge about the source-rock systems around the world in the public arena. In this screening process, the focus is the hydrocarbon source rock itself. Many of these areas have not seen modern drilling and exploration in the past 2–3 decades. Thus, the logging data available from the wells in the basin can range from vintage gamma ray neutron and BKZ resistivity tools (Tingrey et al. 1995) in former Soviet Union countries to more “modern” 70’s to 80’s vintage logging suites. Occasionally, sonic logs pop up in the archive.

TABLE 1: SURFACE SCREENING CRITERIA AND RANKING FOR COUNTRY A.

		Value	Low Ranking High
Surface Considerations	Civil Law Regime	8	
	Low Population Density	8	
	Political Will for Exploration	6	
	Pipeline Infrastructure	6	
	Open Land	7	
	Environmental Issues	4	
	Oilfield Services Availability	2	

The subsurface criteria needed for shale exploration is similar, in a way, to searching for conventional reservoirs. The reservoir needs a hydrocarbon source, a trapping mechanism, some storage capacity, and flow capacity. In the case of shale exploration, the target zone also needs to be effectively stimulated to achieve commercial production rates, making the mineralogy and geomechanics of the specific area play another criterion. The parameters that would be helpful to map and rank (Table 2) on a regional basis would consist of the following:

1. Volume of the total organic content, TOC-h
2. Volume of the storage capacity, Phi-h
3. Volume of flow capacity, K-h
4. Fracability or brittleness index in the target zone
5. Brittleness index of the "seal" interval
6. Volume of total clay
7. Volume of Quartz
8. Volume of Carbonate

TABLE 2: SUBSURFACE SCREENING CRITERIA FOR A BASIN IN COUNTRY A.

		Value	Low Ranking High
Subsurface Considerations	Depositional Environment		
	Geochemistry		
	TOC	1-12	
	TOC-h	40-850	
	Kerogen Type	II	
	Thermal Maturity	<1.3	
	Gas Content/Oil Yield	60 kg/Ton	
	Mineralogy		
	Clay Content	40	
	Calcite/Quartz	Calcite	
	Storage Mechanism		
	Porosity	4-10	
	System Permeability	.01-.1	
	Pressure	>9ppg	
	Temperature	<300F	
	Depth	<4000m	
	Geomechanics		
	Natural Fracturing	6	
	Stress State	6	
	Brittleness	4	

In some regions, not all of these parameters may be determined from the log data alone. However, in most areas, good approximations can be determined of the key parameters, which can be determined using a minimal suite of logs. **Fig. 2** is an example of using a gamma ray neutron BKZ resistivity to derive key shale parameters in a potential gas play. **Fig. 3** is an example of a 70s vintage density-neutron resistivity logging suite to derive the key shale parameters for a shale oil play. In areas where the open-hole log data may be a bit vintage, cased-hole logs can be used to modernize the original log data if the wellbore conditions permit (Pitcher et al. 2012).

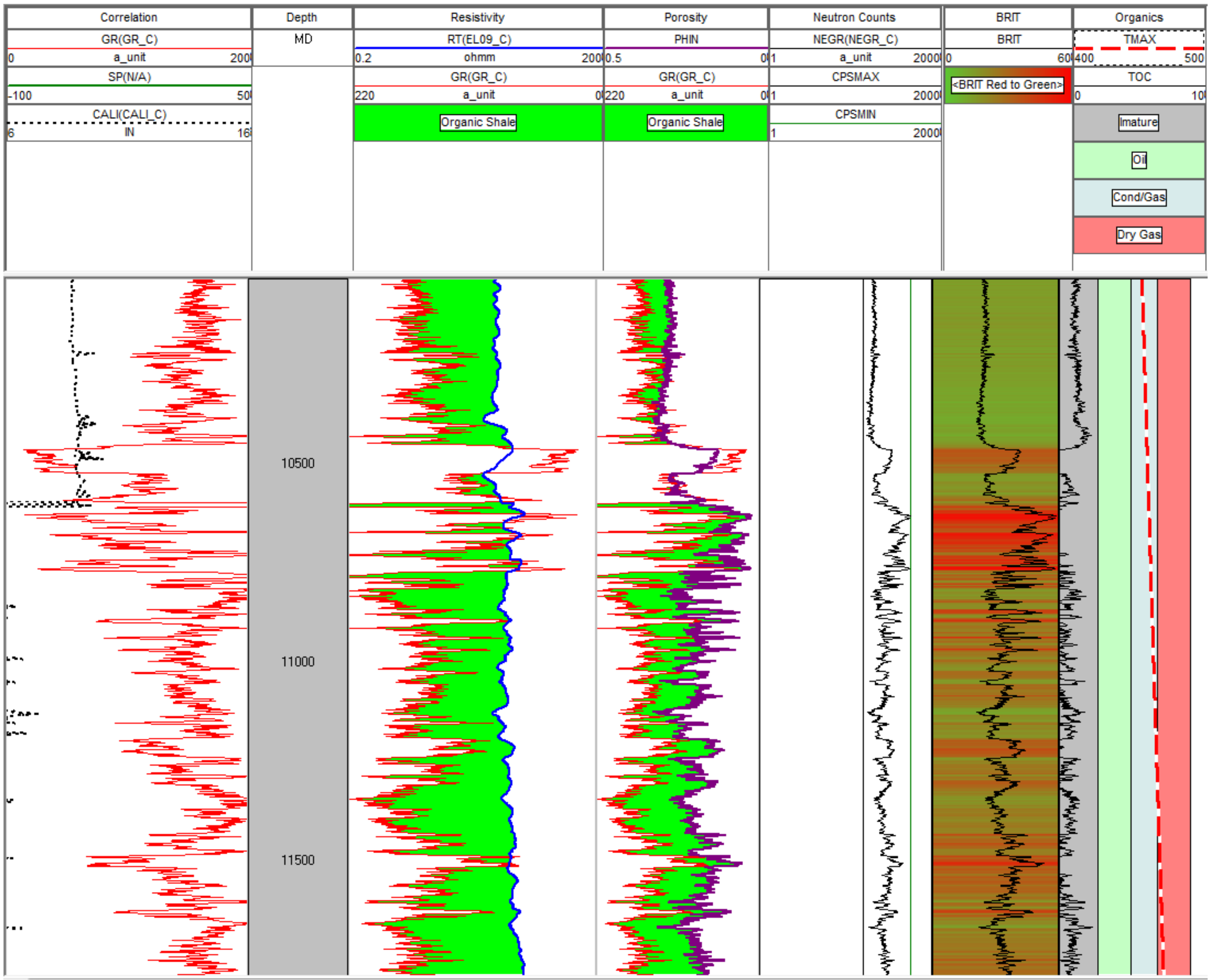


Fig. 2—Shale evaluation analysis using a BKZ resistivity and gamma ray neutron log. Overlays, RT/Inverted GR and neutron porosity derived from the GR-N/Inverted GR. In the BRIT track, the green colors indicate the more ductile intervals, and the red colors indicate the more brittle/fracable intervals. The last track is a computation of the thermal maturity and TOC to be used in the basin subsurface screening criteria.

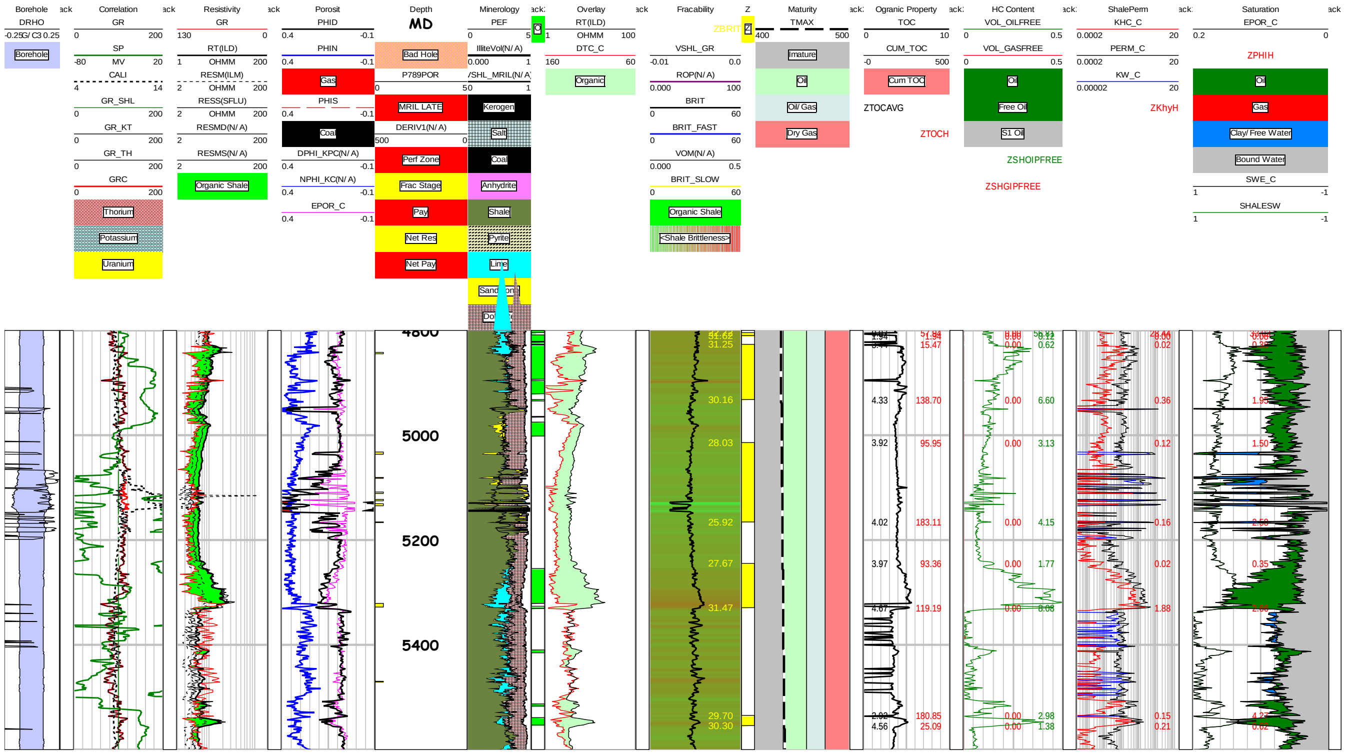


Fig. 3—Shale evaluation analysis in an oil prone shale. The shale parameters of the interval from 5,230–5,360 ft estimates the brittleness at 31%, TOC-h – 119, Kh- 1.88 mD-ft, oil in place of 8.08 MMBO/Section, and a Phi-h of 2.66.

Initial Exploratory Well

The first well drilled into the shale basin may be drilled blind, in that the target depths may not be precisely known. For illustrative purposes, that case will be discussed here.

Where the formation tops are not well defined, the easiest method is to drill a vertical well through the potential shale system. Drilling this well would ordinarily require a very basic pendulum bottomhole assembly with little need of a sophisticated logging-while-drilling suite. A basic gamma ray measurement-while-drilling system on a motor should be sufficient to understand where the top and bottom of the target interval is located. This highlights one of the first issues with shale exploration targets. The zone of interest may be very thick, in the order of many hundreds if not thousands of feet. Determining in a very thick organic-mudstone-rich basin, which is a potentially high-quality zone for further investigation, is part of the new goals for shale exploration.

Once the initial well is drilled, an open-hole wireline-conveyed logging suite is deployed. The logging suite includes basic triple combo, consisting of spectral gamma ray, induction resistivity array, density, and porosity tools. Additional tools include sonic, high-resolution imaging, magnetic resonance logging, and geochemical elemental capture spectroscopy. All of these tools are used to gather information about the basic properties of the target zone. Table 3 describes the tool and its use.

TABLE 3. LOGGING SERVICE AND USE OF DATA.

Logging Service	Evaluation Use
Resistivity - Induction (or Laterolog)	Helps determine saturation & kerogen volume
Density & Photoelectric	Total Porosity, Kerogen, & Lithology Descrimination
Compensated Neutron	Total Porosity & Gas Correction
Spectral Natural Gamma Ray	Thorium, Potasium, Uranium for clay volume, typing, & TOC indicator
Elemental Capture Spectroscopy	Geochemical Mineralogy for matrix corrected total porosity, clay typing (fluid sensitivity)
Oriented Dipole Sonic	stress orientation, vertical & horizontal YM & PR mech props, VTI vs HTI Stress Anisotropy
NMR - T1 & T2	Total Porosity, limits Kerogen Volume, Direct Sw, free Fluid, System Perm, Hydrocarbon Type
Dielectric Porosity	Water filled porosity only, requires matrix corrections from Geochemical Mineralogy
Fresh Mud Imaging	Fracture Characterization (Open, Marginal, Induced), Stress Orientation, Layer Sand Count
Oil Base Mud Imaging	Drilling Induced & wide aperture Fractures only, Stress Orientation, Layer Sand Count

Additional information needs to be acquired at this stage concerning basic rock properties. Rotary-side wall cores are a quick and rapidly-deployed technology to gain good size physical samples of selected rock intervals (Rourke and Torne 2011). Typically, these would be taken as 1.5–in. diameter and 2.31-in. length plugs (**Fig. 4**) in the organic mudstone component, as identified by the open-hole logs.

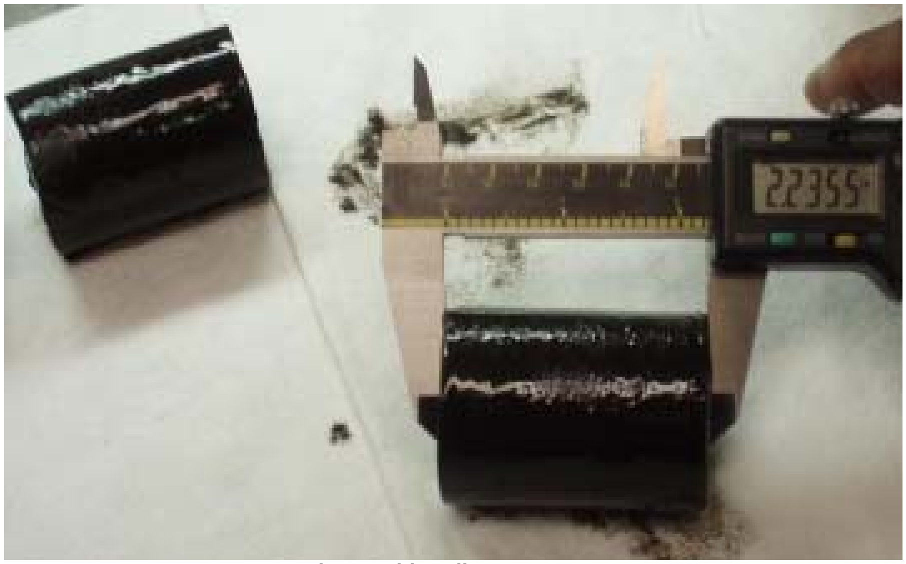


Fig. 4—Sidewall Rotary-Core

These are sent for immediate analysis of vitrinite reflectance and basic geomechanical properties. Other tests performed are typically X-ray diffraction mineralogy, acid solubility, total organic carbon, porosity, capillary suction time, and sorption-desorption isotherms. They can also be sent to an appropriate lab for fluid-sensitivity testing to allow a water-based mud formulation to be derived for subsequent drilling activities in the shale basin (Deville et al. 2011).

Once the open-hole and rotary-side wall coring programs are complete, this initial well is then plugged back and cemented to an appropriate point above the reservoir.

Side-Track Exploration Well

The initial exploration well is then sidetracked and brought back to vertical at an appropriate distance to avoid proximity issues and drilled down to close to the top of the reservoir, as mapped in the original well. At this point, coring begins. There are several coring options available and the most appropriate style, with either traditional core or wireline retrievable core being deployed. Core represents “ground truth” in shales, and the larger the rock volume acquired, the better the information extracted from that volume will be. This is a very important step and deviates from a conventional coring program in that it is not uncommon for extensive amounts of core to be taken. The entire shale interval is typically cored. Core has a myriad of uses in shale evaluation, as represented in Table 4.

TABLE 4: CORE ANALYSIS AND ITS USE IN SHALE EXPLORATION.

Core Analysis	Evaluation Use
S1, S2	Kerogen Type
TOC - Total Organic Carbon	Total Kerogen Volume
GRI Porosity	Milled and sieved core plug for total porosity per GRI published standards
GRI Shale Perm	GRI rrocess matrix perm in nano-darcies, matrix flow capacity
GRI Gas Sauration	GRI process volume left after crushed samples are completely dehydrated, water saturation calibration
XRD - Xray Diffraction	Mineralogy from conventional X-Ray scattering, elements to mineral calibration
XRF-Xray Fluorescence	Mineralogy from X-Ray absorption fluorescence, elements to minerals calibration
ICP-Inductively Coupled Plasma	Most precise elemental spectrum calibration to mineralogy
CST-Capillary Suction Time	Crushed sample flow capacity with different fluids, fluid sensitivity analysis
Brinnell Hardness	Deformation test indicative of potential fracture complexity
Tri-Axial Stress Testing	Vertical vs horizontal YM & PR for stress anisotropy from core
Static YM & PR	Dyanamic log calibration
Ro, Vitrinite Relflectance	Thermal Maturity

Of major significance is the calibration of mineral models for elemental capture spectroscopy (Galford et al. 2009) and the development of a geochemical stratigraphic model for use in later wells (Marsala et al. 2011).

Once the core program is complete, the open-hole evaluation suite is run again to provide logs from the cored sections. Calibrations to core are performed to improve the petrophysical models used in analyzing the shales. This analysis will yield information that will assist in defining the zone of potential productivity from a geological standpoint (Rickman et al. 2008) and identify the target zones for further analysis and data acquisition.

Cased-Hole Evaluation

The next stage of the process is to gain a better insight into the geomechanics of the potential shale reservoir with a view to stimulation. This will require the well to be cased, ideally with the same type of casing envisaged for appraisal horizontal wells and production drilling. This allows the well to be logged using a cased-hole pulsed-neutron tool, which can be calibrated back to the core and the open hole-logs. This will be a valuable calibration point later in the appraisal/development process (Buller et al. 2010).

Once the casing is cemented in place, the lowest potential productive zone identified from the previous analysis is perforated and a Diagnostic Formation Integrity Test (DFIT) is performed (Meyerhofer et al. 1995, Craig et al. 2000). This is a process where a small-scale injection, typically using a single-pump truck on location, provides permeability to mobile reservoir fluid, closure pressure, and reservoir pressure, all of which are critical parameters in understanding how to stimulate the shale zone (**Fig. 5**)

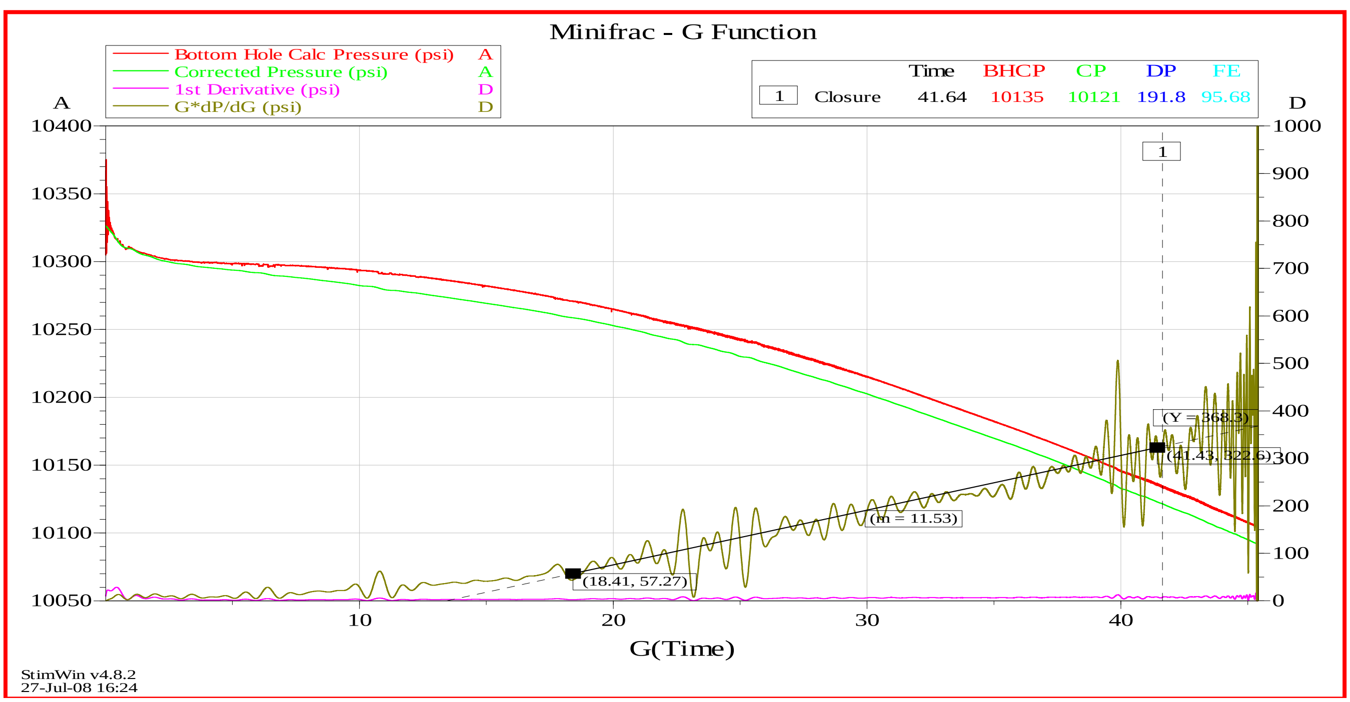


Fig. 5—DFIT Performed in Haynesville Shale.

Subsequent Wells

The process of data acquisition outlined in this work is for well 1 of an exploration program. Several more vertical exploration wells will need to be drilled to properly define the potential shale resource. Typically, these will not require the sidetrack phase, as the top of the reservoir will be detectable either through gamma ray correlation or well-site chemostratigraphy. The chemostratigraphy analysis performed on the first core well will enable subsequent wells to be core without resorting to pilot wells. It will also be used to analyze well placement on subsequent appraisal wells and be of intrinsic value during horizontal well development drilling. Using sidewall core plugs or core plugs taken from whole core allows for the development of an efficient water-based drilling fluid, reducing the environmental footprint and cost of subsequent drilling operations.

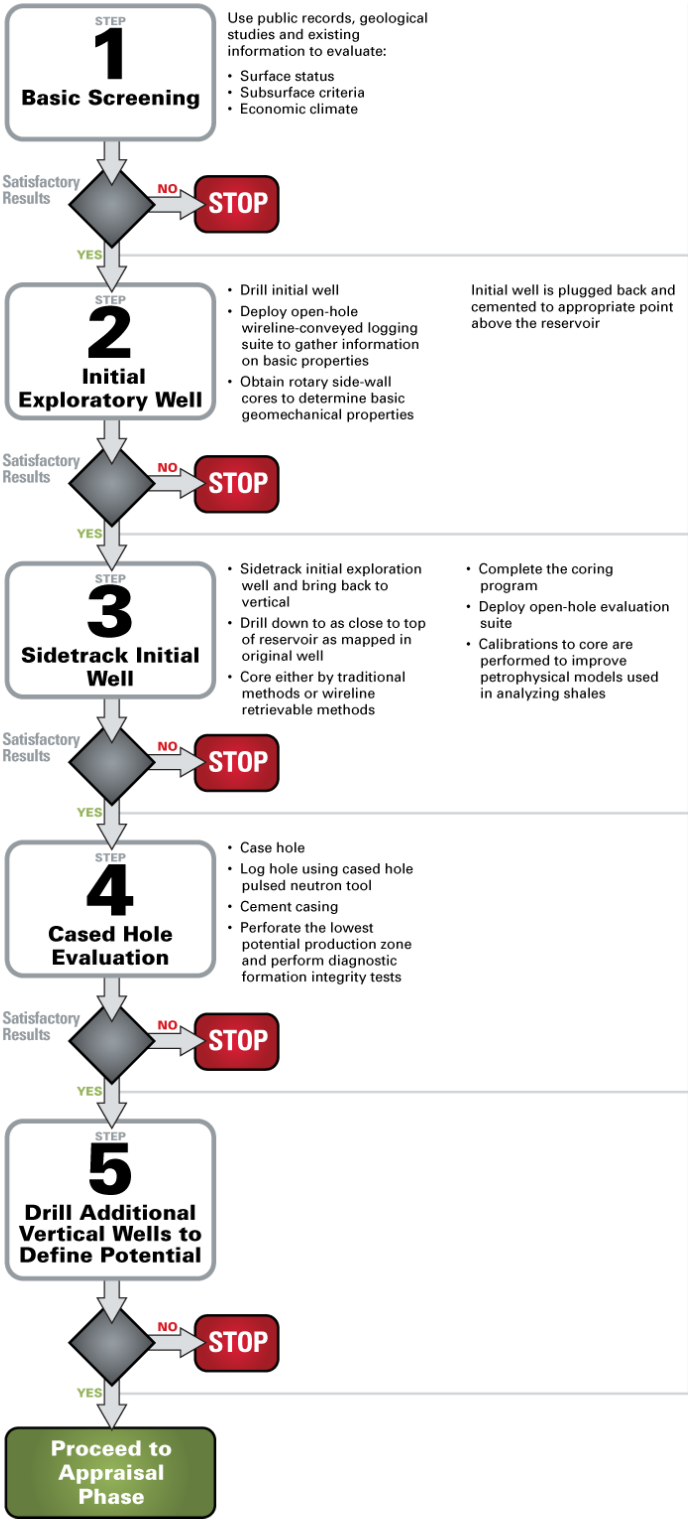
Other considerations, such as how many more exploration wells are cored along with how many exploration wells that are needed is subject to debate, but still the fundamental questions need to be answered. How much gas is in place? How much is recoverable? Is this shale resource exploitable? Haskett and Brown (2010) give a very good analysis of some of the pitfalls involved in the evaluation of unconventional resources, but lateral heterogeneity will be a strong guide to the potential exploration requirements along with initial results.

Workflow

Based on experience in all of the major U.S. shale basins in the U.S., we developed a general shale exploration workflow. This workflow serves as a basis for early shale-basin exploration, with the goal to shorten the learning curve in new shales. The workflow is used as a baseline and then customized to fit the needs of the operator and shale formation. This workflow is designed to:

- Evaluate specific behavior of key factors that impact the system
- Identify potential locations of sweet spots
- Evaluate geochemical and geomechanical parameters
- Determine wellbore geometries
- Evaluate completion and stimulation strategies
- Predict and evaluate well performance
- Optimize wellbore programs

Shale Exploration Workflow: The Path to Appraisal



Questions that must be answered:

1) Is there enough total organic content?
2) Does thermal maturity exist?
3) Is there adequate stimulation potential?
4) Is simple structural environment for horizontal drilling present?

Conclusions

As demonstrated, there is a tremendous amount of information acquired in the shale-exploration process. The process of coming to a yes or no decision on going forward with appraisal and what the potential of the resource is cannot be determined from a single exploration well. The road map for data acquisition is straightforward, and the investment in the data pays off, not only on the single exploration well, but also in data acquisition for longer-term analysis. Each data point acquired builds on the next to give the most complete picture possible for the operator to make the key decision on whether to go to the appraisal phase or not. Understanding the value of each tool that is used and what piece of the puzzle is addressed by that information is critical to a successful shale-exploration program. What is often neglected is information about what not to use. Often, tools are run because they are always run on an exploration project. However, unless defined value can be ascribed to a particular tool, it is always better to leave it out of the evaluation string. An example of this would be a formation fluid-sampling tool or pressure-testing tool. Typically, unless there is a well-defined permeable layer within the shale system, there is little value in running these tools, as the ultra-low permeabilites will not permit functional tests in a reasonable timeframe. This tool, if used, could cost much more than any value it could bring owing to rig-operating costs. This is a prime example of when not to run a tool.

Ultimately, the target formation will determine the most appropriate evaluation suite. The first well is always the most complicated, as this has the most unknowns, but if organic-rich mudstones are the principal target of the evaluation suite, then knowledge of the value that individual elements bring is the first step to a successful-exploration program.

Acknowledgements

The authors would like to express their gratitude to our colleagues past and present who have contributed to this paper.

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