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A two-step analysis can provide the key information needed to design optimal shale completions. The first step is to evaluate reservoir quality, which describes the hydrocarbon potential of a shale. The second step is to evaluate completion quality, which describes stimulation potential. Core analysis provides the basis to help calibrate the results of these two steps. The intersection of good reservoir quality and good completion quality leads to the best chance for success in shale completion. However, a failure to address both reservoir quality and completion quality will jeopardize the achievement of the ultimate goal: optimized production.

A shale reservoir by definition is a hydrocarbon source, reservoir, trap, and seal in a single package. Though similar in outward appearance, no two shales are alike. They are typically complex, heterogeneous rocks with extremely low permeability. Stress anisotropy is commonplace. This calls for the judicious integration of geology, petrophysics, geomechanics, and reservoir engineering to solve the puzzle that will enable the reservoir to yield its prize.

Reservoir Quality
To determine reservoir quality, defined as the hydrocarbon potential of a shale, it is necessary to quantify the amount of hydrocarbon in place and its deliverability to the fracture face. To do this, we must know the organic matter content and type, its thermal maturity, the effective porosity, fluid saturations, matrix permeability, and reservoir pressure.

The hydrocarbon in shale has evolved from thermogenic or biogenic alteration of kerogen, a fossilized organic material that is the source of oil and gas. In addition to providing the hydrocarbon source, kerogen plays a key role in developing reservoir quality in shales. Its degeneration creates pore space that makes up in part for the porosity lost during sedimentary compaction.

Because of its extremely high surface area and affinity for hydrocarbon molecules, this pore space is an excellent storage medium for gas, which becomes adsorbed onto the organic surfaces. In addition, free gas or oil may exist in larger pores, both within kerogen and between mineral grains. Understanding the mix between adsorbed and free hydrocarbons is essential for calculating total hydrocarbon content. Because of the role of kerogen in creat-
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ing pore space and providing hydrocarbon storage, there is a strong correlation between kerogen content and total porosity, hydrocarbon saturation, and permeability. Therefore, kerogen content, or total organic carbon content (TOC), is an important indicator of overall reservoir quality.

Until now, TOC evaluation has involved indirect measurements and correlations. A new-generation spectroscopy measurement obtainable by using the Litho Scanner high-definition spectroscopy logging tool developed by Schlumberger provides a direct continuous measurement of carbon. Enabling the measurement are the tool’s new cerium-doped lanthanum bromide (LaBr₃:Ce) gamma ray detector and advanced pulsed neutron generator. The tool also provides precise concentrations of 18 other elements—including most of the major rock-forming elements—which enable mineralogy to be determined. This is a key factor because when the carbon content in minerals such as calcite and dolomite is subtracted from total carbon, what remains is TOC. With mineralogy and TOC established, the determination of porosity is facilitated and adsorbed gas content can be estimated.

The remainder of the puzzle involves calculating the total hydrocarbon saturation. This is typically estimated from resistivity measurements, the interpretation of which can be uncertain in shales because of low porosity, high clay content, and unknown water salinity. However, the multifrequency dielectric dispersion measurement obtainable with the Schlumberger Dielectric Scanner tool can determine water volume independent of resistivity.

A third advanced measurement can be made by using a new application of the modular formation dynamics tester tool. From advanced interpretation of the pressure falloff following a stress test, it is possible to obtain the permeability and reservoir pressure. This information is not obtainable by conventional methods in reservoirs with very low permeability. Fig. 1 displays the results of an integrated reservoir quality evaluation. This plot summarizes all of the relevant properties that affect reservoir quality, including porosity, permeability, and fluid saturations, which include adsorbed and free gas content.

Completion Quality

Once the reservoir quality has been determined, the completion quality must be quantified. Defined as the effective

Fig. 2—Completion quality analyses are correlated with those of reservoir quality, which subsequently helps engineers design treatment stages (tracks at right). Good and bad treatment zones also are clearly identified. (Logs courtesy of Schlumberger.)
creation of maximum surface area per unit of reservoir volume during fracturing, this potential derives from the formation's mechanical properties such as near- and far-field stresses and rock strength analysis. An integrated mechanical earth model (MEM) is created from drilling, log, and core measurements. The latest generation sonic log measurements, delivered by an advanced acoustic scanning tool, provide critical input to the MEM. By measuring axial, radial, and azimuthal slownesses in the formations, the tool can provide the vertical and horizontal Young's modulus and Poisson's ratio figures needed for the layered nature of the shale—which is calibrated to multistress tests of the core samples. In addition, the tool helps identify natural fractures, which can also be imaged precisely by using formation microimager tools.

Stress analysis is a critical input to the MEM. The tectonic stresses that control the stress anisotropy can be evaluated by analyzing drilling-induced fractures, as well as observations of shear wave splitting and crossover from dipole dispersion analysis. Additionally, discrete closure stress measurements performed by modular formation dynamics testers can confirm the stress profile and model from advanced acoustics, core analysis, and borehole image data. The presence and orientation of natural fractures also provide valuable information for designing hydraulic fractures. Including the natural fracture swarms with those of the hydraulic fractures, maximum reservoir contact can be obtained.

By combining the results of the reservoir quality step and the completion quality step, a “truth table” can be developed on which the selection decisions for the most promising completion zones are based. Data matches between the reservoir quality and completion quality results enable identification of the best hydraulic fracturing targets. The value of this approach is immense. Fig. 2 demonstrates the integration of reservoir quality and completion quality for the identification of good and bad treatment zones and optimization of treatment stages.

**Core Analysis**

Using selective core analysis on the zones identified by a heterogeneous rock analysis technique, it is possible to acquire valuable information on reservoir quality and completion quality. TOC calculations can be verified, as can porosity estimates. Total and clay-bound water saturations can be confirmed, as well as matrix permeability, rock texture, and mineralogy. Other valuable core-derived data include those obtained from multistress tri-axial compression testing, proppant embedment studies, and fluid compatibility studies. If conventional core data has gaps or is missing altogether, large-diameter cores from a newly developed large-volume rotary sidewall coring tool can be used.

**Conclusion**

Recently, an operator in the Marcellus Shale play discovered that two of 11 fracture stages completed were contributing 70% of a well's production. Evidence pointed to the arbitrary way the completion stages were placed at even intervals across the completion. By redesigning subsequent treatments according to the match between reservoir quality and completion quality data, the targets with the highest production potential were identified. An offset well in which completion was designed using stress mapping delivered the same production rate as the original well, but with a 50% completion cost reduction because of selective perforating. During previous treatments, the operator experienced screenouts on several stages and sustained costs of USD 300,000 each to mitigate the screenouts. Since switching to the new workflow, the operator has experienced no screenouts.

By using a systematic workflow and comprehensive formation evaluation, operators in shale plays can improve completion effectiveness, reduce completion costs, and boost production rates, well productivity, and field profitability. JPT