SHALE RESERVOIR EVALUATION IMPROVED BY DUAL-ENERGY X-RAY CT IMAGING

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ABSTRACT

The rise of unconventional shale plays as an economically feasible oil and gas resource has created an unprecedented opportunity and challenge for laboratory core analysis providers. By some estimates, more than 80% of the core samples being extracted from North American fields are from shale formations. Core analysis has become an integral part of most unconventional exploration and development projects because the data is considered essential to petrophysical interpretation, completions design, reservoir modeling, and reserve estimation. A major difficulty facing most operators is that shale core analysis using traditional methods can be a slow process, yielding data that may arrive too late to assist in time-critical business decisions.

The well data reported in this paper is an example of results obtained on 24 similar wells in the Catatumbo basin of Colombia. The purpose of the work was to characterize the rock type and quality from available core samples penetrating the La Luna shale. A secondary objective was to provide information on similarities or differences between this formation and other more familiar formations from North America.

Digital Rock Physics (DRP) analysis provides a way to obtain the needed data more rapidly. DRP analysis of shales usually involves three stages, each providing visual and quantitative information to help select a smaller representative rock volume for the next analytical stage. Stage 1 analyzes whole cores or cuttings; stage 2 analyzes samples from cuttings to plug size; and stage 3 analyzes samples at pore scale in 3D with ultrahigh resolution. In this report, we will examine just the first stage of DRP for whole or slabbed core, using the CoreHD technique developed by Ingrain. The method is based on dual-energy X-ray CT imaging and usually requires only a few days to complete, often quickly enough to be used for completion decisions. The technique has been deployed at remote drill sites, where the core was analyzed within minutes or hours of being brought to the surface. By combining the dual-energy X-ray CT imaging with other data such as core spectral gamma scanning and X-ray fluorescence (XRF) tests, we can compute more valuable information like total organic content (TOC), porosity, mineralogy, and "brittleness" index. An example is presented where results from scanned whole core are compared to plug sample measurements and show excellent agreement in most locations.

INTRODUCTION

In 2012, the Colombia government's National Hydrocarbon Agency (ANH) initiated a project with Ingrain for digitizing and analyzing about 10,000 meters of core from the archives. The well discussed in this paper was selected as an example of this larger project. The Tibu-176 well is from the Catatumbo Basin in Colombia and was cored primarily in the La Luna Formation. This formation has been a world class source rock, but its potential as an unconventional reservoir rock is just starting to be recognized.

The La Luna formation is Cretaceous in age (like the Eagle Ford of S. Texas) and widely distributed along the Catatumbo Basin. It is the source rock in the basin and approximately 180 ft thick with TOC averaging about 9% by volume (Kuuskra, et al, 2011).

TECHNOLOGY AND METHODS

Digital Rock Physics (DRP) developed by Ingrain was applied in the La Luna-1 well following a detailed workflow especially designed for the characterization of shales. During Phase1, CoreHD® dual energy X-ray CT imaging was carried out with a voxel resolution of about 0.5 millimeter. From this imaging, a continuous log was computed of high-resolution rock bulk density (RHOB) and photoelectric factor (PEF) using a process described Vinegar, 1986 and Coenen and Maas, 1994. Bulk density is an indicator of porosity and organic matter content, while PEF is an indicator of mineralogy. The data acquisition and interpretation was completed within about 3-4 days from when the core was received.

The conceptual model used to describe organic mudstones and quantify mineralogy and organic content is shown in Figure 1. This model has been modified slightly from the original as presented by P. Day, 2012. The RHOB and PEF information can be used to define shale facies (Figure 2). This process separates the data into four or more facies classes and was used to characterize and identify the greatest reservoir potential in the La Luna formation. This facies classification was described in Walls and Sinclair, 2011. In this example there are six RHOB-PEF classes represented by the following colors;

- Yellow: sandstone, low density
- Grey-green: sandstone, higher density
- Green: shale, higher TOC and/or porosity, higher silica
- Red: shale, higher TOC and/or porosity, higher carbonate
- Black: shale, lower TOC and/or porosity, higher silica
- Blue: shale, lower TOC and/or porosity, higher carbonate.

In addition to RHOB and PEF curves, spectral gamma ray data was acquired for this well. Combining all available data and interpreting the results allows for the computation of mineralogy, TOC, and brittleness. Calibration data from X-ray fluorescence (XRF), X-ray diffraction (XRD) is acquired at various depth points.

The total organic content (TOC) from the whole core was computed using an empirical relationship to RHOB and spectral gamma scan data. Mineralogy was computed from a combination of gamma ray and PEF using traditional log analysis methods. Brittleness index (BI) is a term used to describe the relative tendency of a rock formation to fracture as opposed to deform gradually in response to tensile or shear stress (Rickman, et al, 2008, Guo, et al, 2013). In this paper we use the definition proposed by Rickman in which BI depends upon static Young's modulus and Poisson's ratio with an additional assumption that the relevant moduli and Poisson's ratio can be taken from normalized solid mineral properties. In practical terms, greater BI means the rock is easier to hydraulically fracture.

RESULTS

In Figure 3, Track 2 shows the computed mineralogy values indicating a high calcite fraction and medium to high silica content depending on depth. Clay content is relatively low. Track 4 shows the CoreHD facies. Red and green colored facies represent higher porosity and organic content. Track 9 shows a computation of brittleness index. The data shows a pronounced sweet spot in total organic content (TOC) of about 7 to 9% by volume at a depth interval from approximately 7870 to 7900 feet.

Elsewhere in the cored interval we see that organic material is highly variable over a range from less than 2% to over 10% by volume. Computed TOC was also shown to agree well with measured TOC from high resolution scanning electron microscopy (red dots in Track 8). The facies colors (Track 4) are determined by establishing simple threshold values of RHOB and PEF as shown in Figure 2 on the left. These thresholds are subjective but can be useful to quickly spot variability and zones of interest.

DISCUSSION

The data from this well is fairly typical of other wells in the Catatumbo Basin that penetrate the La Luna formation. In particular it shows favorable TOC over a wide depth range. The computed brittleness index (Track 9) shows values generally greater than 80 on a scale of zero to 100. This suggests that the formation should be relatively easy to frac. For comparison, pure quartz with no porosity has a BI of approximately 120, which represents a practical upper limit for this quantity.

To compare this well to data from more familiar North American plays, we have shown in Figure 2, on the right, an outline of the RHOB-PEF region occupied by wells that have been analyzed previously in the Wolfcamp and Eagle Ford formation, Texas. The outlined regions illustrate at least qualitative similarity to both formations but overall the well looks more analogous to Wolfcamp based on its wide range of PEF values.

SUMMARY AND OBSERVATIONS

The Tibu-176 well from the Catatumbo Basin in Colombia was cored primarily in the La Luna Formation. Using a combination of RHOB, PEF, and spectral gamma data, key shale reservoir quality indicators of mineralogy, total organic content (TOC), and brittleness index have been computed. Based on the data the following observations can be made;

- The well exhibits moderate to high total organic content over its entire length with the highest TOC zone between 7870 and 7900 feet.
- Mineralogy is primarily carbonate and silica with low clay content.
- Computed brittleness index is generally higher than 80 (scale 0 to 100) suggesting the formation should be easy to frac.
- A substantial fraction of the well has RHOB less than 2.5 g/cm3, which may be associated with good quality organic mudstone formations (Walls and Sinclair, 2011).
- RHOB-PEF data from this well is similar to that from the Wolfcamp formation of west Texas.

While the rock properties appear favorable as compared to other known shale plays, the overall economic potential also depends on formation pressure, fluid content, and other geologic conditions. Work from multiple operators is underway now to better assess these characteristics so that the play can be effectively developed and contribute the long-term success of the Colombian E&P industry.

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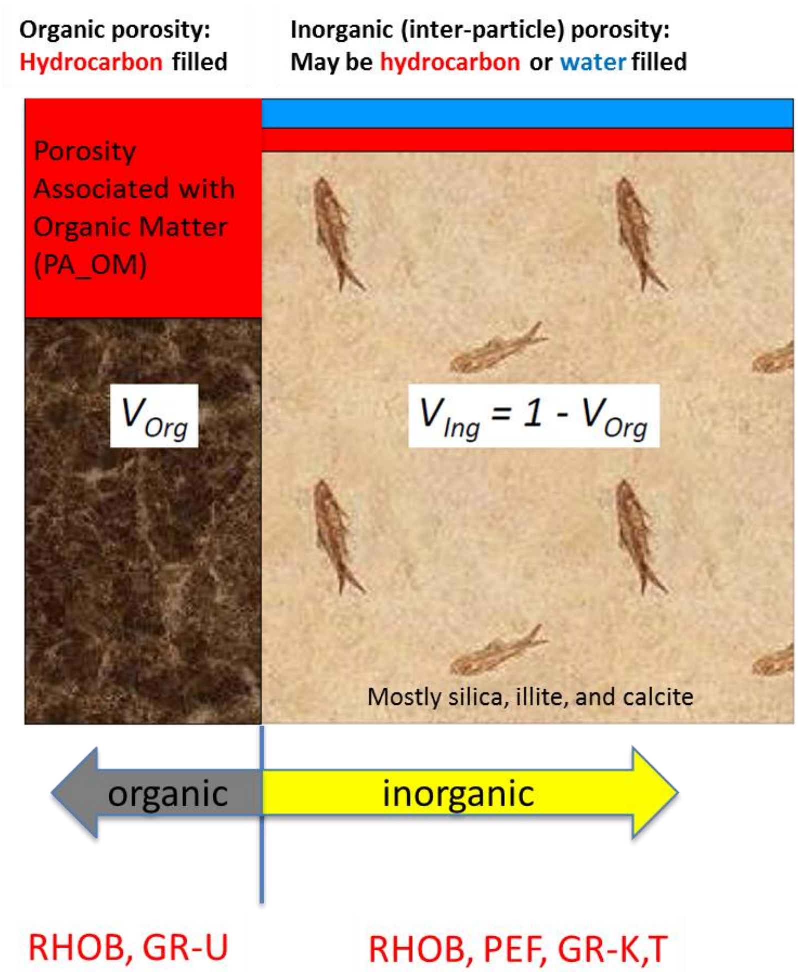

Figure 1. Rock model for organic mudstone as used to interpret core measured RHOB, PEF, and spectral gamma data (modified from Peter Day, Marathon Oil, SPWLA Black Shale Conference, 2012). The inorganic component is quantified based mainly on RHOB, PEF, and uranium-free spectral gamma. Organic components are quantified based mainly on RHOB and the uranium gamma data.

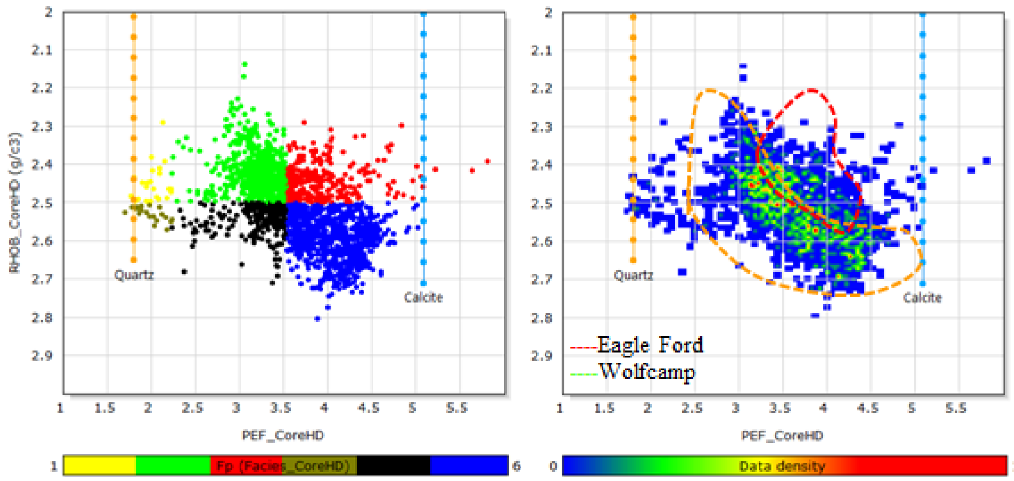

Figure 2. On the left: CoreHD facies are based on RHOB and PEF thresholds and can be used to divide the data into zones, which correspond to mineralogy and porosity or TOC variations. Each region in the cross-plot is assigned a specific color and those colors are displayed in depth domain in Figure 2, Track 4. Each dot represents about 0.05 feet of core. On the right: RHOB versus PEF data colored by population density from the Tibu-176. La Luna Fm, Catatumbo Basin, Colombia. The color bar represents how many data points are present in any given region of the cross plot. The red color means a high concentration of data points and the blue color means few data points are present. Outlines show approximate region of this plot corresponding to typical wells from the Eagle Ford and Wolfcamp plays.

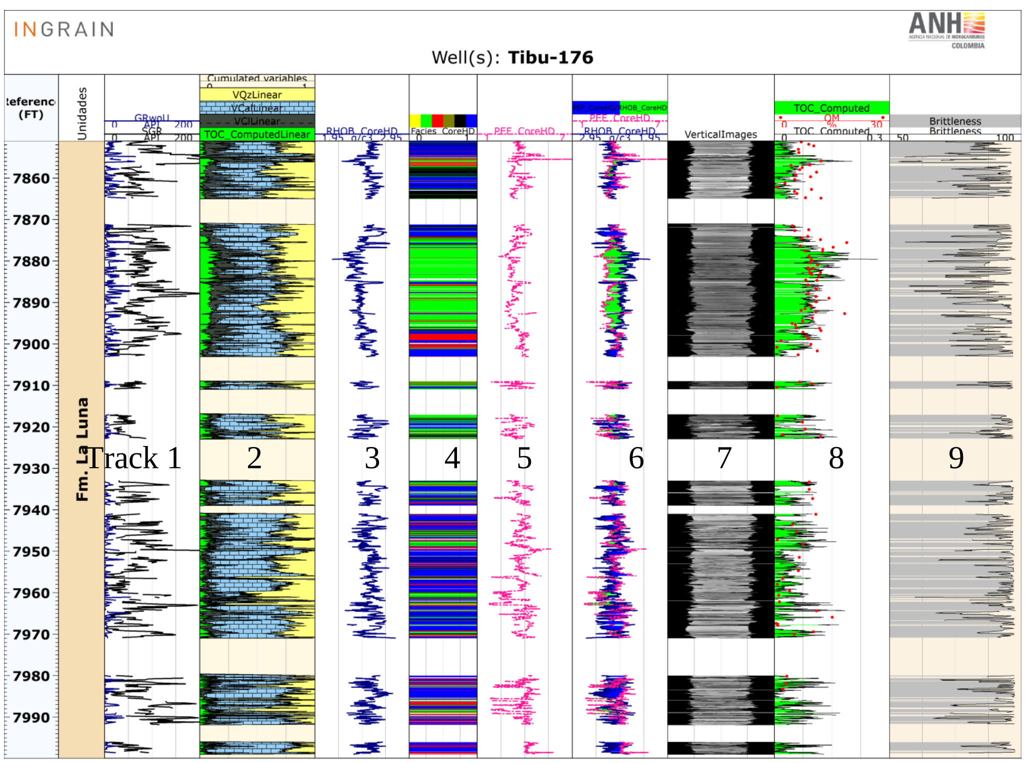

Figure 3. CoreHD output data and computed curves. Track 1, spectral gamma; Track 2, computed mineralogy; Track 3, RHOB; Track 4, CoreHD facies; Track 5, PEF; Track 6, RHOB-PEF crossover; Track 7, core CT images; Track 8, computed TOC, Track 9, computed brittleness index.