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Quantifying Gas Saturation with Pulsed Neutron Logging—An Innovative Approach

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Abstract

In reservoir surveillance, gas saturation is routinely monitored both in gas reservoirs for reservoir performance and in saturated oil reservoirs to prevent gas coning or to optimize infill drilling well placement. This paper presents a new pulsed neutron technology and method that enable the quantitative monitoring of the gas saturation variations to address these reservoir management issues. One of the key features of the newly designed pulsed neutron tool is the new type of Lanthanum Bromide (LaBr3) detectors. The extra-long spacing of the far detectors provides a larger volume of investigation that is more representative of the actual reservoir condition. The quantitative aspect of the measurement is achieved by using the ratios of the detector counts, so that the rock matrix effects are diminished, as opposed to the traditional sigma measurement, which can be influenced significantly by the rock matrix properties. This new tool and data interpretation methodology have been tested in both clastic and carbonate reservoirs with encouraging results. This paper presents an overview of the technology and some field application examples.

Introduction

Pulse neutron (PN) technology has existed for nearly 50 years now (Youmans et al. 1964) and during that time sigma (Σ) has been employed as the workhorse of saturation (S) monitoring for both oil and gas reservoirs in high salinity environments. In 1971 Clavier et al. suggested the requirements for a quantitative saturation analysis as being:

1. Reservoir porosity (with accuracy) $\phi > 15\%$
2. Reservoir lithology is free shale; i.e., clean formations
3. Formation water salinity > 100 Kppm

The primary source of uncertainty, which results in a qualitative rather than quantitative saturation answer outside these conditions, is not the statistics on the measurement but rather the uncertainty on the various input parameters required for the analysis, as defined in Eq. 1.

$$S_w = \frac{\left(\Sigma_{\log} - \Sigma_{ma}\right) - \phi\left(\Sigma_{hc} - \Sigma_{ma}\right) - V_{sh}\left(\Sigma_{sh} - \Sigma_{ma}\right)}{\phi\left(\Sigma_w - \Sigma_{hc}\right)} \quad (1)$$

Where S is saturation, V is volume, and the subscripts indicate log reading (log), matrix (ma), hydrocarbon (hc), shale (sh), and water (w).

While these conditions are equivalent to $\Delta\Sigma \approx 6$ CU (cross-section unit) between water and hydrocarbons at any particular reservoir porosity, it is noted that in the case of a saturated oil reservoir the contrast of interest is not between the gas and water (which is larger) but between the oil and gas (which is much smaller, and so more difficult to quantify.) In the most obvious application, steam flood of a heavy oil reservoir, this 6 CU requirement sets the minimum porosity requirement at $\phi_{min} > 27\%$; which is often difficult to meet.

In the application considered in this paper, the conditions are generally poorer than the guidelines suggested by Clavier et al. (1971) with porosities in the 20% to 30% range, while the expected gas sigma $\Sigma_g \approx 8$ CU and oil sigma $\Sigma_o \approx 21$ CU. To compound these difficulties, the sands are generally of the poorer quality with higher shale volumes. At a porosity of 20%, a sigma sensitivity of only about 2.6 CU exists; less than half of that suggested by Clavier et al. (1971). Further complications arise from the mineralogical uncertainties present; high sigma minerals such as pyrite and siderite exist and clay minerals in the shales are variable with chlorite, kaolinite and illite (Table 1).

Table 1—Mineral properties interested in this application

Mineral	Density	Capture cross section	MDPN NB
	gm/cc	C.U.	units
Pyrite	5.01	89.9	11.87
Siderite	3.94	52.3	44.69
Kaolinite	2.59	12.8	49.57
Chlorite	2.88	25.3	52.95
Illite	2.64	15.5	49.49
Quartz	2.65	4.3	19.38

Note: MDPN stands for multi-detector pulsed neutron and NB is for neutron burst. The values in the last column represent the expected response of the new measurement: ratio of counts during the neutron burst (in ratio units).

The literature review showed that various techniques have been proposed to reduce the uncertainty in calculated saturations under complex mineralogy conditions by effectively using a level-by-level varying sigma matrix parameter. In a 2003 paper, Zalan et al. used a technique in which a sigma matrix is derived from the open hole density, neutron porosity and gamma ray logs using a coefficient regressed from data recorded in reference wet zones within the field. Simpson and Truax (2010) suggest expanding the material balance equation to use multiple mineral volumes derived from capture spectroscopy measurements. Although those approaches could improve the performance of Eq. 1, uncertainties in the calculated Sw could still be significant due to the effect of input parameter uncertainties. A more detailed uncertainty analysis for Sw determination from Eq. 1 is provided in Appendix A. The objective of this paper is to describe a new approach based on the neutron burst ratio for gas saturation quantification.

New methodology

Recently, new measurements have emerged (Trcka et al. 2006), based on multi-detector pulsed neutron technology (MDPN) where measurements sensing a larger volume of the neutron gamma transport field are made using an array of detectors providing larger spacings between the detectors than conventional instruments. These larger sensed volumes result in higher measurement sensitivities to several formation properties, including gas saturation (Badruzzaman et al. 2004; Guo et al. 2010).

The instrument employed for the trial described in this paper comprises four spectroscopic Lanthanum Bromide detectors (LaBr3) and a fast neutron detector distributed axially along the tool body coupled to high count rate electronics. The instrument generates two new measurements useful in formation evaluation; a fast neutron normalized burst (NB) and capture ratio (NC), derived from the nearest (proximal) and furthest (long spaced) detectors as well as four detector carbon-oxygen (C/O) and sigma measurements.

Characterization of all these measurements is accomplished using full 3D neutron-gamma transport response modeling for the exact wellbore geometry and borehole fluid conditions, which existed during logging of the well. The instrument measurements are calibrated by a multi-point calibrator prior to the logging; this calibrator performs a calibration of both the magnitude and sensitivity of the instrument readings.

Interpretation of the measurements follows mathematically from the characterization data along traditional lines except for the handling of shale in both the C/O and formation gas interpretations. In both cases analytical shale characterization and petrophysical processes have been implemented to strengthen the mathematical definition of the shale effects and reduce the reliance on subjective aspects of the analysis within the saturation calculation workflow.

Previous applications of MDPN technology have been published by various authors (Zett et al. 2008; Ansari et al. 2009; Marsh et al. 2010; Brackenridge et al. 2011; Zett et al. 2011; Zett et al. 2012a; Zett et al. 2012b; Bertoli et al. 2013). In this paper, we address a new MDPN instrumentation with its associated nuclear attributes and its specific application to complex mineralogical environments.

The significant differences between this methodology and that of traditional sigma are demonstrated in **Fig. 1** and a more detailed uncertainity analysis for the new methodology is provided in Appendix B.

- Traditional sigma:
  - Very little difference between sandstone oil and sandstone gas; i.e., difficult to be used to differentiate gas from oil, especially if reservoir porosity is low to intermediate.
  - Large effect of mineralogy, i.e., uncertainties in mineralogy determination have significant effect of Sw using Eq. 1.
- New methodology:
  - Large dynamic range between sandstone oil and sandstone gas; good for gas quantification.
  - Small mineralogy effect, except pyrite
  - Works in much lower porosity reservoirs

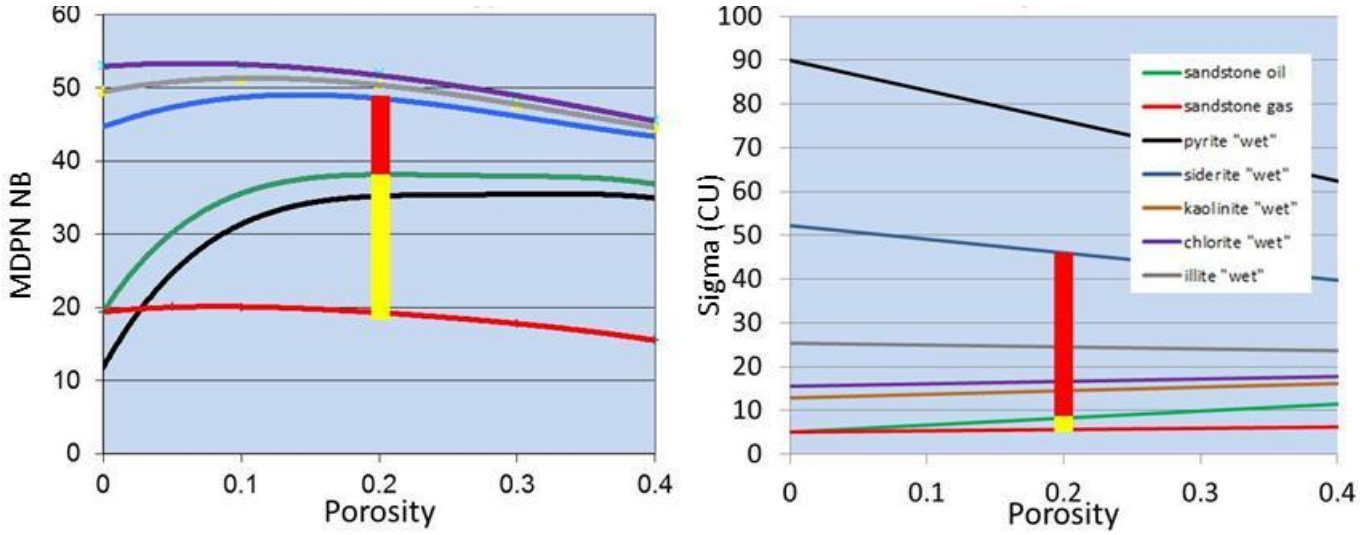

Fig. 1—A comparison of the new methodology (left) vs. traditional sigma (right).

Note: The green and red lines represent the response for sandstone oil and gas lines, respectively, while the other colored lines represent the "wet" response for the various minerals considered; black is pyrite, blue is siderite, grey is illite, purple is chlorite and brown is kaolinite. In the new methodology the gray line is exactly over the top of the brown line so only one is visible. The yellow bar indicates the gas sensitivity of each system at a porosity of 20% while the red bar illustrates the sensitivity to siderite.

Analysis technique

En-route to arriving at the saturation profile from the measured nuclear attributes, one always goes through some important questions. Satisfactory answers to these reinforce the validity of the measurements and interpretation; these are:

- Does the characterization match the formation, wellbore, completion, borehole conditions?
- Was the tool operating correctly?
- Was the measurement seeing the formation?

The characterization was constructed for the exact conditions encountered; casing size, weight, borehole size, cement and borehole fluid. Furthermore, the peaks and spectra tracked correctly throughout the log interval and attest to the proper functioning of the tool.

The modeled characterization is interpolated with the formation porosity to construct the analysis envelope within which the measured curve will respond. Shale is characterized in-situ and enables the mathematical handling of the envelope in proportion to shale volume. **Figure 2** below shows the shale characterization function derived in situ from the whole logged interval of one well. Essentially, this curve added to the sandstone characterization "wet" line and represents the in situ shale effect on the measurement. The spread of data points about the function illuminates the variance it introduces into the saturation computation although the spread at higher porosities is a mathematical anomaly resulting from the method of calculation and the presence of gas.

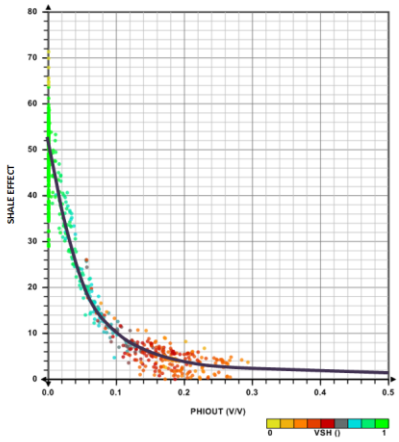

Figure 2—Illustration of the derivation of the in situ shale characterization; the thick line represents the derived shale correction function from the measured data points.

The main indicator that the measurement is seeing the formation is "coherence." Coherence is the synchronous motion of the measured curve and the envelope; that is, they move and sway together with the changing properties of the reservoir. This is an important observation because the measured curve and the envelope are independently constructed, so their synchronous motion is a strong indication that

- the tool is seeing the formation, and
- the reservoir model agrees with what the tool sees in the reservoir.

Figure 3 below illustrates this coherence; the measured curve follows the wet line and departs toward the gas line when it sees gas. It returns and follows the wet line when the porosity decreases; when the wet line moves left, the curve moves left. When the wet line moves right, the curve moves right. The curve position with respect to the envelope yields the gas saturation. The contact movement is also readily apparent when compared with open hole density and neutron porosity data.

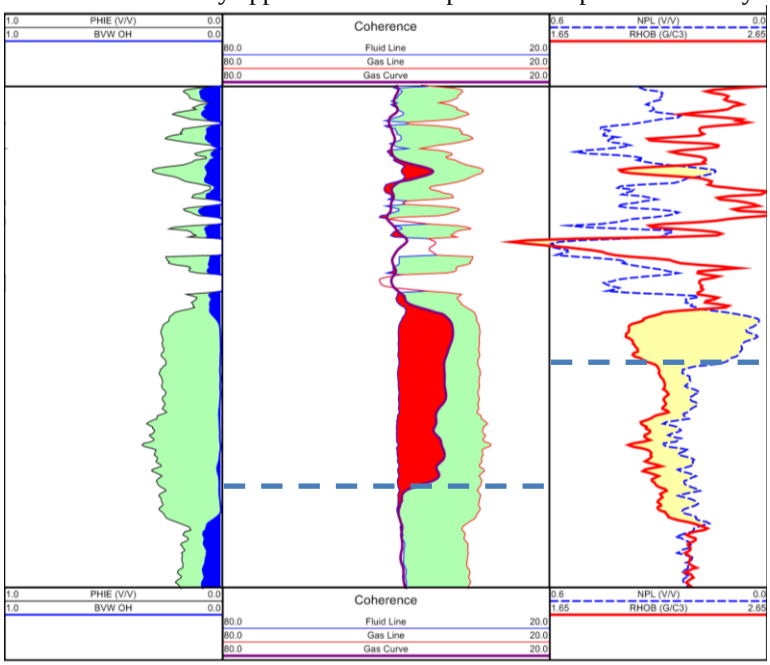

Figure 3—Illustration of the analysis envelope. Tracks 1 and 3 contain open hole pore volumes and data, respectively; while Track 2 displays the analysis envelope and measured curve. The red line of the envelope is the gas line and the blue line is the liquid line.

Results

The MDPN NB measurement has been field tested in wells completed in fluvial sandstone deposits, where pressure is supported by natural aquifer and gas cap expansion drive. The reservoir lithology is complex (containing shales and other minerals like pyrite and siderite) and porosity averages 26%. The main objective of the evaluation was to determine gas-liquid contact locations and determine the gas saturation profile in the sands; particularly the thinner sands overlying the main oil producing interval. In all, three wells (**Figs. 4, 5, and 6**) were investigated to gain a spatially significant view of gas cap development over the field. From Figs. 4, 5 and 6, the location and magnitude of gas saturations are intuitively obvious from the displays, which helps engineers to better understand reservoir performance in terms of which of the overlying sands are in pressure communication with the main reservoir and which are not, or are in restricted communication; information which is key in reservoir management.

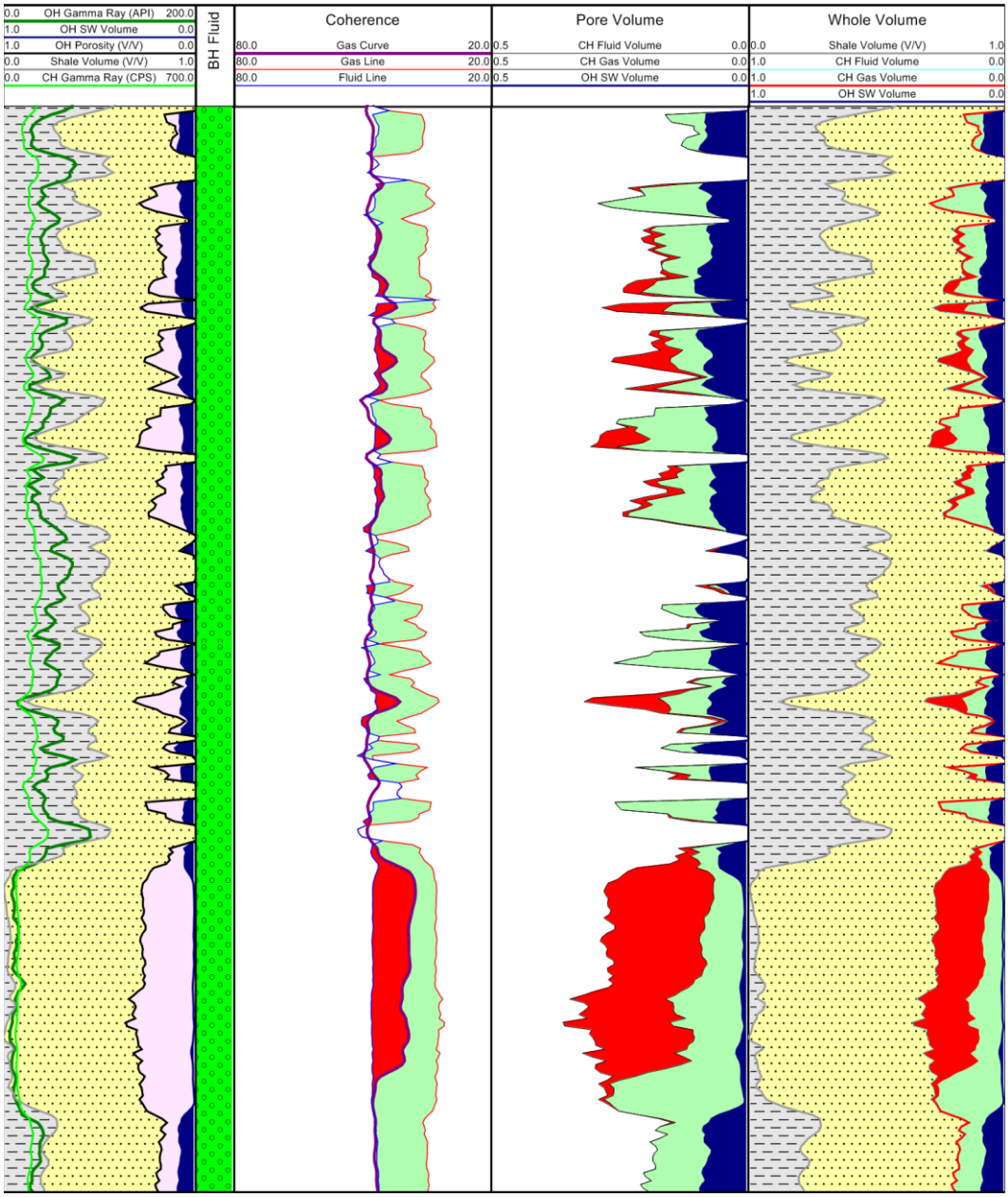

Figure 4—Example Well-1, Track 1 displays the supplied open hole volumetrics and correlation curves while Track 2 displays the borehole fluid condition. Track 3 displays the analysis envelope while Tracks 4 and 5 display the pore volume and whole volume results, respectively. The location of the gas/liquid contact is observed and an indication of which sands are developing gas caps is obtained. Remaining oil saturation can also be estimated.

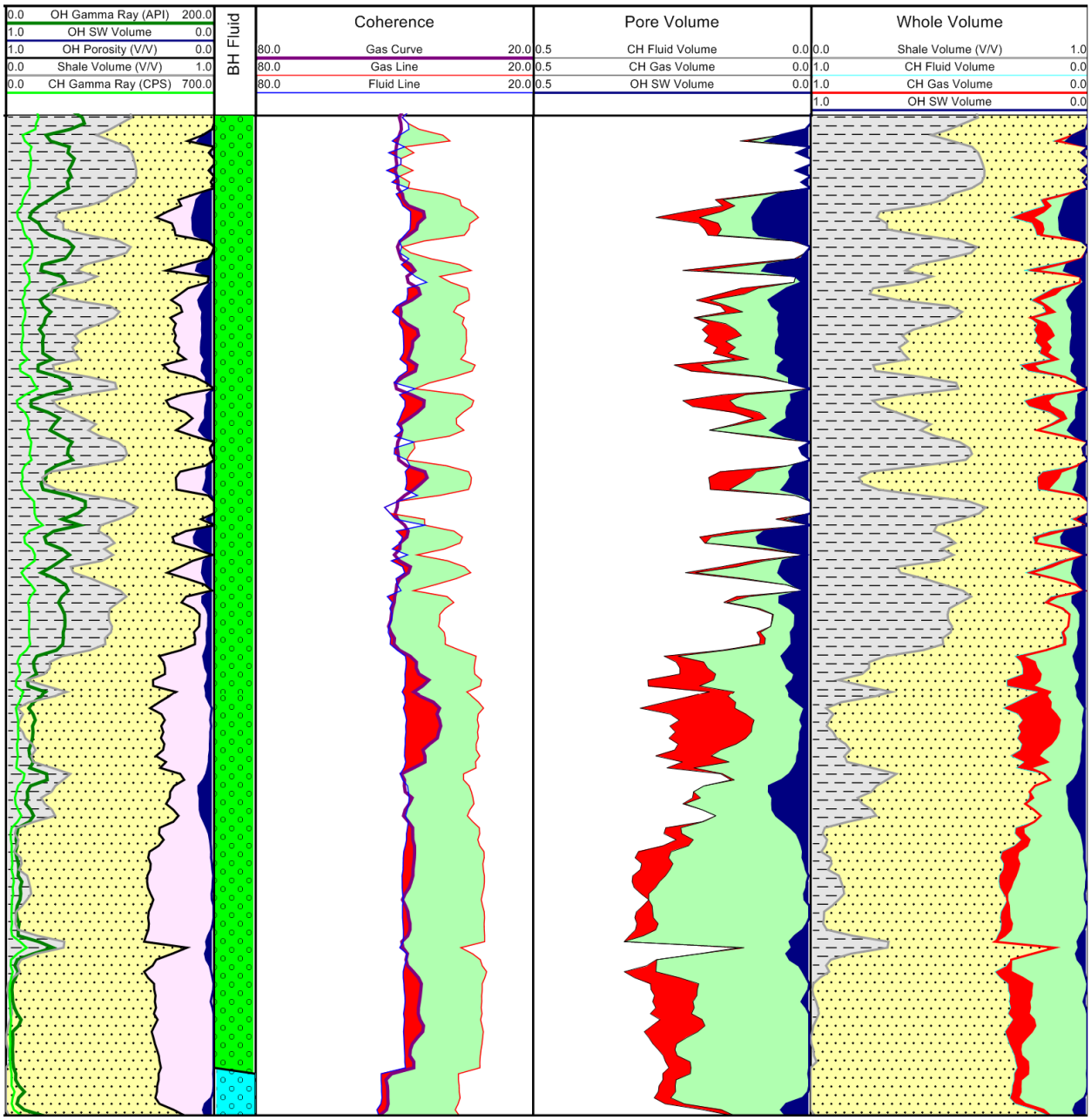

Figure 5—Example Well-2. Similar plot to Fig. 4, this figure shows that a gas cap is being developed at the top of the main sand.

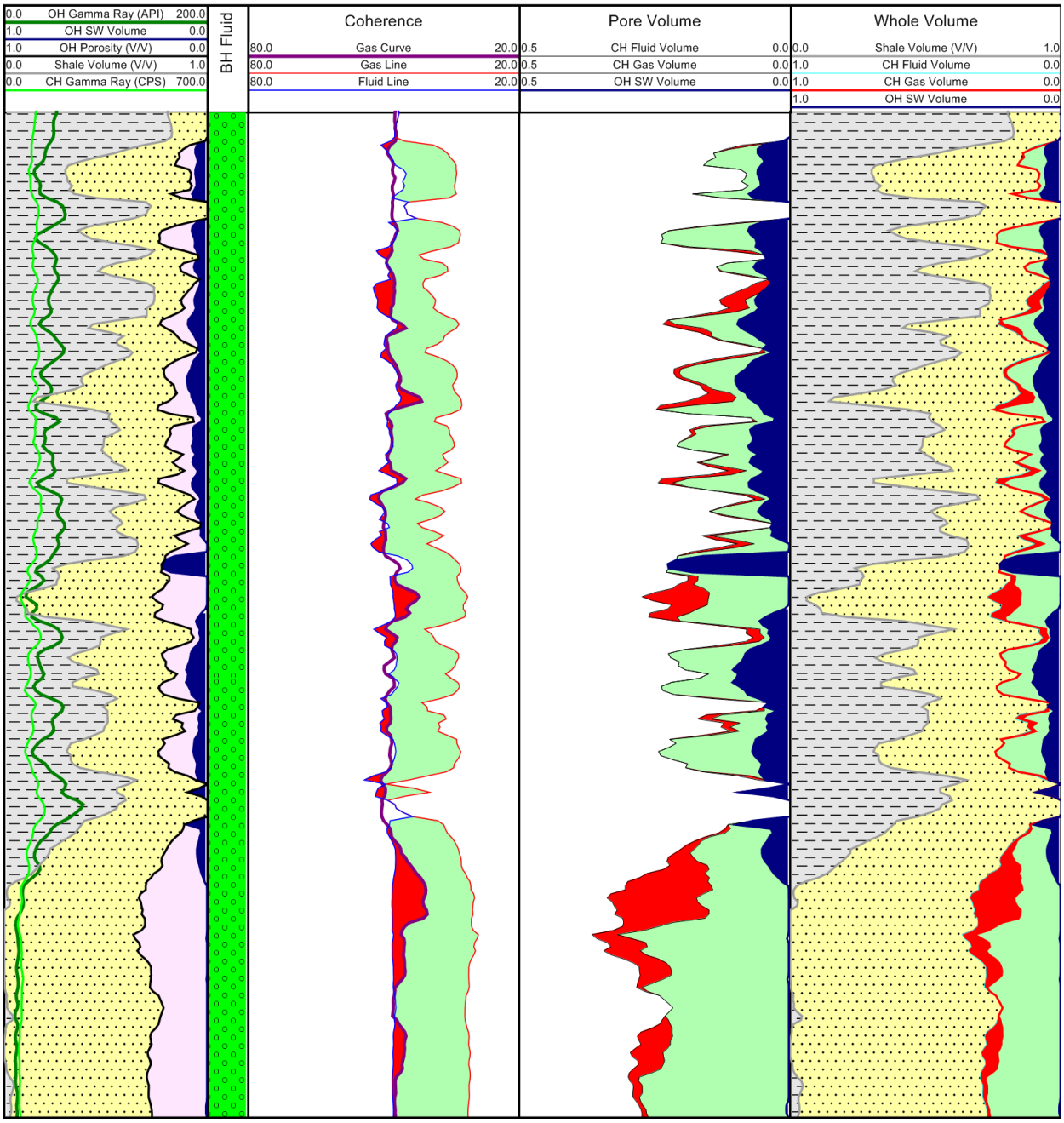

Figure 6—Example Well-3. A similar plot to Figs. 4 and 5, this figure shows that a gas cap is being developed at the top of the main sand.

Summary

A new measurement based on MDPN is presented with field examples showing the applications of the technology. The new technology is robust in reservoirs with complex lithologies when compared to the sigma analysis technique. The analysis technique is intuitive with a clear connection between the derived saturations and the petrophysical inputs; shale volume and porosity, the Monte Carlo response characterization, the derivation of the in-situ shale characterization, and the generation of the analysis envelope. The trial results have been encouraging under difficult conditions and warrant further testing to determine the limits of the technique in terms of porosity range, completion complexity and lithological environments. In the applications tested to date, performance of the technique has been in line with expectations and no special logging practices or procedures have been required.

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Appendix A
Uncertainty Analysis of Traditional Sigma Measurement

In an effort to gauge whether this latter technique would result in acceptable accuracy in calculated saturations uncertainty, calculations were undertaken in this paper. By using the published uncertainties for elemental yields of a spectroscopy tool, and summing in quadrature in the correct proportions, an uncertainty figure for the volume of clay, pyrite and siderite was calculated; this data is presented in **Table 2** and does not include any additional errors introduced by the element weights to mineral volumes models employed; the clay volume uncertainties derived are in line with the work of AlRuwaili (2005). With these uncertainties the resulting uncertainty in capture units can be calculated simply by multiplying the mineral volume uncertainty times its respective effective macroscopic capture cross section contribution at reservoir porosity. Since the material balance equation is a simple linear system, the effective contribution is the difference between the mineral matrix value and sandstone matrix value times 1 minus the porosity and represents the sigma difference observed when sandstone is completely replaced by the other mineral. The resulting uncertainty from each component is then easily computed by dividing by the measurement sensitivity and a single value of matrix uncertainty is computed once again by summing the individual components in quadrature.

The results of this process are startling when examined; the reader is reminded that the statistics on a measurement divided by the sensitivity simply defines the *precision* of the measurement but the *accuracy* is influenced by the contribution of ALL the uncertainties. The uncertainties in saturation introduced from ONLY the sigma matrix parameter under these conditions, listed in Table 2, ranged from 0.439 to 0.475 V/V depending on which clay mineral was assumed to be present; the lowest being Kaolinite and the highest being Chlorite. In essence, the saturation measurement has an uncertainty range of 0.88 (+- one standard deviation) and a dynamic range of 1. This figure of course does not include the contributions from the more conventional sources such as statistics (which can be reduced by logging multiple passes), diffusion correction error, porosity error, sigma oil and sigma gas parameter errors (none of which can be reduced by logging multiple passes); the effect of which will further increase the uncertainty. This situation is further compounded by work performed by Badruzzaman (2007[5] and 2010[4]), which suggests there are significant errors inherent in gas saturations reported by sigma calculations attributable to other influences such as neutron transport phenomena in gas filled formations.

Table 2—Uncertainty in gas saturation resulting from mineralogical uncertainty using sigma methodology

Mineral	Uncertainty	Effective Sigma	Product	Saturation Uncertainty	Total	Total	Total
	V/V	C.U.	C.U.	Sw V/V	Kaolinite	Chlorite	Illite
Pyrite	0.011	67.92	0.74712	0.287354	summation	summation	summation
Siderite	0.0222	37.84	0.83967	0.32295	summation	summation	summation
Kaolinite	0.0315	6.24	0.19681	0.075696	summation		
Chlorite	0.0315	8.4	0.264936	0.101898		summation	
Illite	0.0315	16.24	0.51221	0.197004			summation
Measurement sensitivity @ 0.20 porosity = 2.6 C.U.					0.438861	0.444131	0.475057

Appendix B
Uncertainty Analysis of the New Technology

Before going on to discuss the results it is prudent to go through the same error propagation exercise for this new technique as was done for sigma. To accomplish this, full modeling was performed for the wellbore geometry to be logged for each of the required minerals and from this the results, presented in Fig. 1, were obtained (an observation of this Monte Carlo characterization process is that ALL neutron transport and diffusion effects are inherently accounted for in the results). The conditions used were exactly the same as those used for the sigma analysis; porosity of the reservoir being 0.2 V/V and sandstone lithology as the basis. The results of the error propagation analysis are presented in **Table 3** and remarkably the saturation error range is now reduced to 0.024 to 0.026 depending on which clay mineral is present; an improvement factor of almost 20 times in accuracy over sigma under these conditions. Note also the similarity in response of the three clay types, virtually removing the need for clay type identification and differentiation within the shale.

Table 3—Uncertainty in gas saturation resulting from mineralogical uncertainty using the new methodology

Mineral	Uncertainty	Effective contribution	Product	Saturation Uncertainty	Total	Total	Total
	V/V	Ratio units	Ratio units	Sw V/V	Kaolinite	Chlorite	Illite
Pyrite	0.011	4.67	0.052	0.0027	summation	summation	summation
Siderite	0.0222	10.31	0.229	0.0120	summation	summation	summation
Kaolinite	0.0315	12.30	0.387	0.0204	summation		
Chlorite	0.0315	13.68	0.431	0.0227		summation	
Illite	0.0315	12.27	0.387	0.0204			summation
Measurement sensitivity @ 0.20 porosity = 18.94 Ratio units					0.02393	0.02592	0.02389

The picture is even clearer if the results are presented as a ratio of the sensitivity to a particular mineral divided by the sensitivity to gas; this is shown in **Table 4** where the last column is a figure of merit comparing the relative sensitivity of sigma to the MDPN measurement for each mineral component; the biggest offender is pyrite which has over 100 times more effect on sigma than on the new method.

Table 4—Comparison of relative sensitivities; sensitivity to a particular mineral divided by the sensitivity to gas, of sigma and the new methodology

Mineral	Relative sensitivity		Merit figure
	Sigma	MDPN NB	
Pyrite	26.12308	0.246568	105.9467
Siderite	14.55385	0.544351	26.73616
Kaolinite	2.4	0.649419	3.69561
Chlorite	3.230769	0.722281	4.473009
Illite	6.246154	0.647835	9.641577

In fact, the situation is improved so dramatically that gas saturations calculated using the new methodology employing just porosity and a generic shale volume curve are less uncertain than sigma calculations using the “best minerology” solution from elemental spectroscopy.