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Pulsed-Neutron System Evaluates MPZ, ROZ In West Texas CO_2 Flood

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ARLINGTON, TX.–The Goldsmith-Landreth San Andres Unit (GLSAU) carbon dioxide flood in the Permian Basin was among the initial applications of a new, multidetector, pulsed-neutron system for measuring reservoir fluid saturation.

The basic reservoir description was provided from core data and open-hole logging, and measurements from multidetector pulsed-neutron were used to derive total porosity and gas saturation from the detector array data. Pulsed-neutron logging provided real-time analysis of CO_2 placement in the reservoir flood, with much higher well density coverage.

After years of waterflooding at Goldsmith-Landreth, the main pay zone (MPZ) reservoir was at residual oil saturation by the mid-1980s. In 2009, Legado Resources began a pilot study to assess recovering the MPZ residual oil with CO_2 flooding. In contrast to gravity-drained miscible flooding, the pilot used more active flooding in addition to waterflooding to produce the residual oil. As part of the enhanced recovery program, Legado also targeted the residual oil zone (ROZ) below the oil/water contact.

There are many cases of oil/water contacts with residual oil in place below the original production horizons in the Permian Basin of West Texas. Tectonic uplifts may be the root cause, where ancient waters entered the basin and naturally waterflooded hydrocarbon-bearing rock. Core data from the GLSAU reservoir indicate that the oil saturation in the ROZ below the oil/water contact is very similar to the MPZ after years of waterflooding. In fact, it appears that that "nature's waterflooding" in the ROZ was as efficient as the waterfloods implemented by operators in the MPZ above the oil/water contact.

The pulsed-neutron reservoir analysis technology was used to monitor CO_2 position and movement, as well as define the base of the residual oil. The system features an array of three gamma detectors (near, far and long). The near and far spacings are used for sigma and C/O logging, while the long spacing adds enhanced sensitivity to gas and porosity.

A qualitative "quick-look" processing recipe was devised to visualize gas in place, reservoir porosity, and features such as the base of the ROZ using the ratios of the near and long detectors. Sections of the reservoir with gas in place were assigned an ad hoc gas saturation typical of West Texas CO_2 floods. The parameters of sigma-based oil saturation and porosity calculations were matched to core data. In an effort to measure gas saturation more accurately, a follow-up project was conducted that built and processed detailed Monte Carlo models based on specific reservoir rock and fluid data.

Given an independent measurement of gas saturation from the detector array, the sigma measurement can be used for oil/water saturation, yielding two inputs in a three-phase fluid solution. In contrast, previous techniques applied in steamfloods with freshwater used the sigma measurement to derive the gas (steam) saturation and C/O to derive the oil saturation. The sigma-MDPN technique is more robust than the sigma-C/O model and can be logged in a single logging pass.

MPZ And ROZ Recovery

Gravity-stable CO_2 floods have been operational in the Permian Basin for decades, injecting CO_2 to build a gas cap to and push the miscible oil down so it can be recovered. However, the flooding approach adopted for GLSAU entrains the carbon dioxide in the oil as it is enters the reservoir through the injection wells. This miscible oil phase has a larger volume and lower viscosity, and therefore a portion of it is washed along with the flood to producing wells.

Understanding these reservoir dynamics is important in devising an analysis program. In this case, some moved oil may be seen in zones with higher oil saturation, but in most of the flushed (and virgin) zones, the oil saturation changes only a few percent, so the analysis objective is focused on CO_2 placement and saturation.

Pulsed-neutron systems were designed for monitoring conventional reservoirs and fluids (e.g., oil, saltwater and gas) by nuclear reactions with elements such as hydrogen, oxygen and carbon. Analysis has been extended to three-phase saturations in steam floods utilizing sigma logging for steam versus liquids, and C/O logging for oil versus water. Carbon dioxide as a third fluid phase poses some special concerns for three-phase analysis.

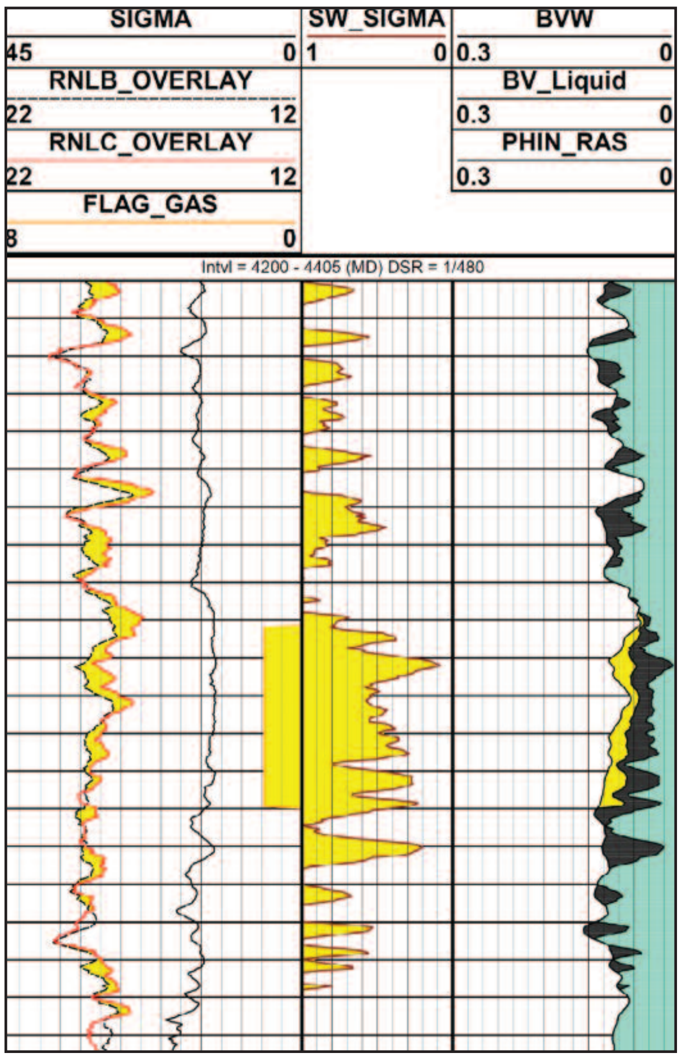
This San Andres dolomite reservoir has porosities ranging between 6 and 16 percent. The produced water is also used as injection water, and has 40-50 kilo parts per million (kppm) sodium chlorides (NaCl). Because of the GLSAU reservoir's depth and temperature, the CO_2 has a density of 0.77 grams per cubic centimeter (g/cc) and moves in the reservoir similar to gas by displacing the water. PNC measurements respond to the lack of hydrogen, the displaced saltwater, and the very low capture cross-section of carbon dioxide. For pulsed-neutron spectroscopy (C/O logging), the response is ambiguous in measuring CO_2 saturation versus water saturation (i.e., CO_2 versus H_2O).

In general, the statistics and uncertainty of C/O logging pose some practical limits when applied to low-porosity reservoirs such as GLSAU. However, C/O logging has been applied to CO_2 floods in other fields in a qualitative sense to target the moved oil as carbon dioxide sweeps the reservoir rock. In those applications, the hydrogen excavation effect (i.e., comparing total porosity to neutron porosity) was exploited to map gas in place.

Most wells in the GLSAU reservoir do not have open-hole logs, so the challenge was to measure porosity and CO_2 saturation. As a first step, a quick-look analysis was developed us-

FIGURE 1

Quick-Look Analysis Results



ing curve overlays from the near- and long-spaced detectors to spot CO_2 gas in place. To improve the accuracy of the analysis, details of the reservoir, well bores and reservoir analysis construction were used as inputs into a Monte Carlo N-particle transport code software package. The computer-based models generate datasets for solving the inverse problem, and the spatial response of the detector array is mapped to estimate porosity and CO_2 saturation.

After solving for total porosity and gas saturation (S_g), sigma water saturation (S_w) is solved for all three fluids. Given the low porosity, three reservoir fluids, and water salinity uncertainty, the S_w results are semiquantitative. However, even with error bars, S_w calculations can cross-check gas in place and define the base of the residual oil zone.

There are aspects of the GLSAU reservoir that help refine analysis accuracy for CO_2 saturation and porosity. For example, the reservoir rock is fairly consistent (mostly dolomite, with some traces and thin layers of anhydrite and gypsum). Formation water and original oil have similar density and hydrogen content, and the miscible phases can be broken into CO_2 and original oil for the analysis, making estimates of CO_2 saturation independent of oil saturation. In addition, GLSAU wells have very good cement jobs, which combined with high-quality cement bond logs yields a potent analysis of wellbore conditions.

FIGURE 2A

RNLC Response Model for Porosity and CO² Saturation

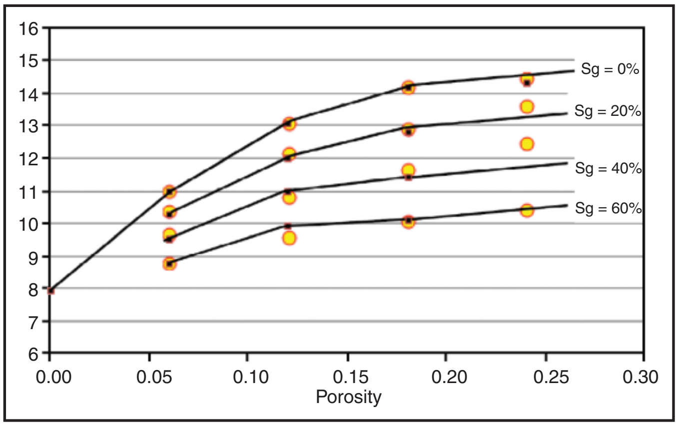
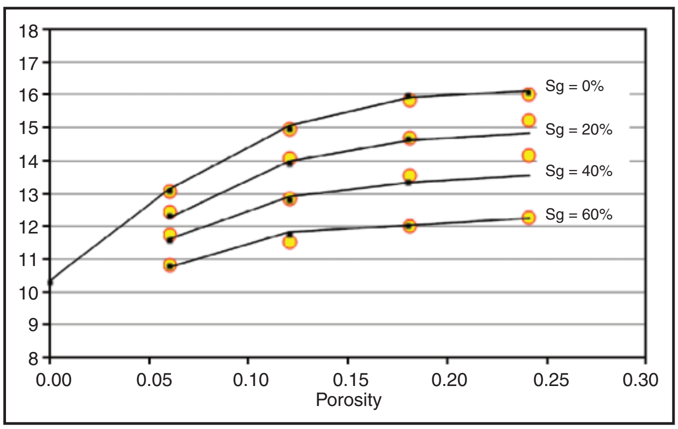


FIGURE 2B

RNLB Response Model for Porosity and CO² Saturation



RAS System Description

The multidetector pulsed-neutron system was operated in the sigma logging mode. The neutron pulse was 200 microseconds and decay data were collected in 19 time bins for each of the three gamma detectors: near, far and long.

To set up the quick-look overlay, the first step was to normalize the near-to-long capture ratio (RNLC) and the near-to-long ratio during the neutron burst (RNLB) in the water-filled zones below the ROZ to the zero porosity in the cap rock. The overlay of RNLC and RNLB from the quick-look analysis is plotted in the first track in Figure 1 along with sigma responses, with gas shading when RNLC is less than RNLB to flag gas in place.

The second track (SW_SIGMA_GAS) is water saturation from sigma using two fluids: a mixture of oil and carbon dioxide versus saltwater. In the third track are bulk volumes using neutron porosity as the effective porosity (PHIN_RAS). Where the RNLC-RNLB overlay and sigma indicate gas in place, the bulk CO_2 volume was assigned an ad hoc value based on typical saturations. From the plot, one can note reservoir features such as CO_2 in place and the base of the ROZ.

Cement Bond Analysis And Wellbore Uncertainty

Wellbore uncertainty is an incessant concern in cased-hole reservoir analysis. Although cement quality is very good in the GLSAU wells, there was still uncertainty about bore hole size. Previous modeling and practical analysis suggest that cement has a presentation similar to shale for pulsed-neutron measurements. Therefore, enlarged hole sizes will cause porosity to read too high and gas saturation to read too low.

The good cement quality and fast dolomite formations allow imaging of the formation arrival in the cement bond log data. The quick-look analysis can be checked by noting the cement bond log. Given a maximum travel time for the dolomite (e.g., 60 microseconds per foot) and the bit size, a “bad hole” flag can be set for sections with enlarged wellbores.

Solving For Gas Saturation And Porosity

To map the measurements into gas saturation and porosity, the computer code MCNP was used to model the nuclear tool’s response. Computer experiments were designed for a dolomite reservoir with an 8.75-inch well bore with cemented and centralized 7.0-inch, 23 pound casing. The modeled fluids were oil, CO_2 (0.77 g/cc) and saltwater (50 kppm NaCl).

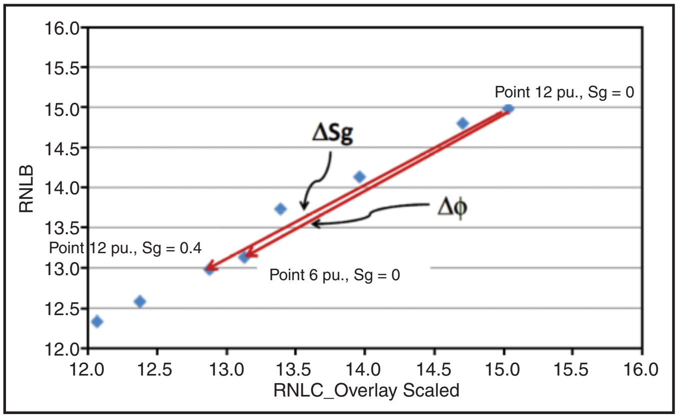
Figure 2A diagrams the modeled data for RNLC, while Figure 2B diagrams the modeled data for RNLB. Both response fans show sensitivity to porosity and CO_2 saturation. But while they have a similar porosity response, the RNLC has a larger sensitivity to gas. With the computer models, a sufficient number of particles can be sampled to get statistically useful results. With the logging tool, this relates to logging speed and precision. The system logged the GLSAU wells at 12 feet/minute with 0.208 average RNLC deviation and 0.122 average RNLB deviation. Neutron porosity precision was ±0.6 porosity units in the range of 0-18.

Simultaneously solving for porosity and CO_2 saturation from the RNLC and RNLB responses is problematic because the responses are so similar. Figure 3 is a cross-plot of RNLB and RNLC for the modeled data. One can see the similarities in the parametric difference vectors, with the change in porosity from 12 to 6 percent, and the change in gas saturation for 12 percent porosity from 0 to 40 percent S_g.

It is necessary to dig deeper to transform the dataset for more independent parameters. The difference in the ratios RNLB and RNLC can be linked to gamma rays from inelastic scattering present only during the neutron pulse (i.e., RNLB). Typically, inelastic gammas are resolved in C/O logging, but the inelastic gammas can be stripped from the wider pulse widths. The inelastic count rates for the near and long detectors are resolved and placed in a ratio (RNLI). The inelastic stripping process increases the statistical uncertainty of the RNLI compared with

FIGURE 3

Cross-Plot of RNLC and RNLB



RNLB (the precision of RNLI is 0.62 average deviation).

Figure 4 shows the cross-plot of RNLI and total porosity (PHIRT). The z-axis colors are based on sigma. The response fan is superposed on the cross-plot, given the average deviation of RNLI in the well. The precision of the CO_2 saturation at 12 porosity units is 12 saturation units.

FIGURE 4

Cross-Plot of RNLI versus Total Porosity With Gas Response

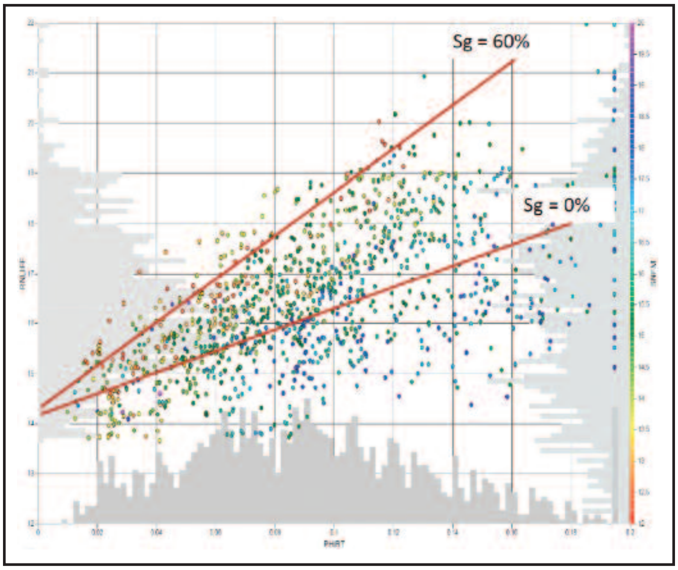


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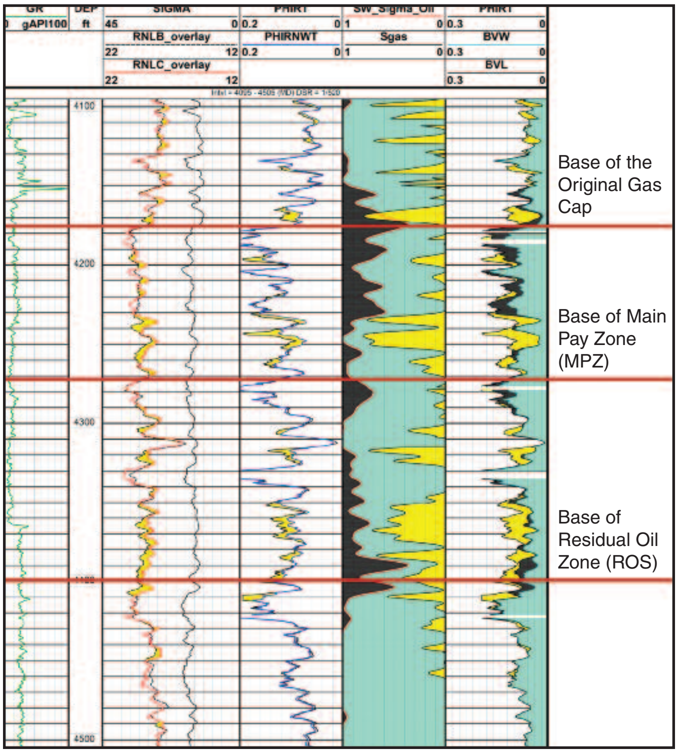
FIGURE 5

Plot of Example Analysis Results



To reduce the variables for the sigma S_w calculation, PHIRT and CO_2 saturation were used to calculate an "excavated" porosity. In this manner, the volume of the CO_2 is moved to the rock matrix and the S_w sigma calculation can be run for oil versus saltwater. The lowered PHIRTX adds to the uncertainty of the S_w calculation. When salinity uncertainty is added, the S_w results are semiquantitative, but are still useful for determining levels in the wells, such as the base of the ROZ.

Figure 5 shows the analysis results across the reservoir from one of the wells. Track 1 is the correlation with natural gamma ray. Track 2 is the quick-look overlay with sigma, RNLB overlay and RNLC overlay, with RNLC normalized to RNLB. Porosity is in Track 3 (PHIRT and neutron porosity). Track 4 is fluids with CO_2 saturation and S_w from sigma and PHIRTX solved for oil versus saltwater (SW SIGMA OIL). Track 5 is bulk volumes, with PHIRT, bulk volume water, and bulk volume liquids.

The ROZ and main pay zone sections of the well are marked on the plot. CO_2 is noted in zones with higher S_g in the ROZ and in the lower MPZ. The top of the reservoir trends to lower porosity, and the higher gas saturations in this section are related to the original gas cap.

FIGURE 6

Cross-Section of Three Wells Depth-Flattened By Correlating Upper Facies

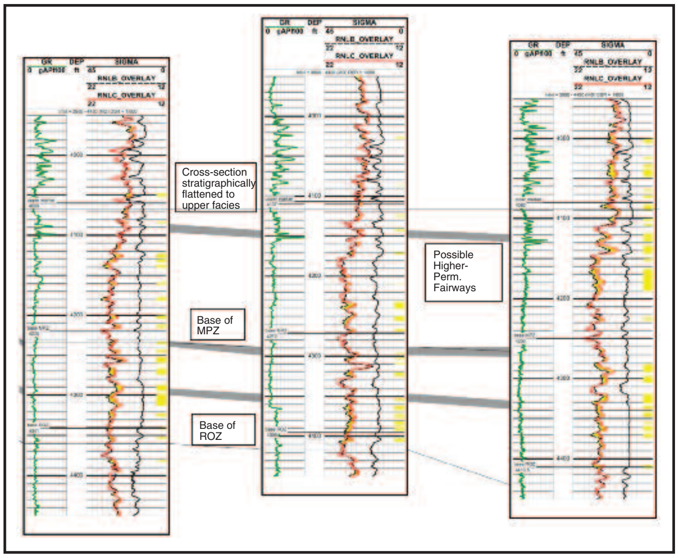


Figure 6 provides a second example using a cross-section of three wells on a north-to-south line. The cross-section has been stratigraphically flattened by correlating the upper facies near the top of the reservoir. These wells are separated by rows of injection wells. By correlating injection profiles (in the injection wells) and pulsed-neutron logging response, several higher-permeability fairways are marked on the cross-section. Also correlated on the cross-section is the base of the ROZ and gas in place.

The high well density allowed a "close to 3-D" reservoir analysis using cased-hole pulsed-neutron logging. Along with identifying the gas in place, the system mapped reservoir porosity and fabric trends to enable a high-resolution, real-time analysis of reservoir conditions in the GLSAU CO_2 flood. ❐

Editor's Note: Kinder Morgan acquired the 6,000-acre Goldsmith-Landreth San Andres Unit from Legado Resources in June for $285 million. This article was adapted from a technical presentation at the Society of Petrophysicists & Well Log Analysts' 54th Annual Logging Symposium, held June 22-26 in New Orleans.

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