APPLICATION OF A NEW MULTI-DETECTOR PULSED-NEUTRON SYSTEM IN A CO_2 FLOOD OF A MATURE FIELD

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ABSTRACT

In 2012, the Reservoir Analysis Sonde (RAS) pulsed-neutron system was introduced by Hunter Well Science and Allied Wireline Services. Along with Sigma logging and carbon-oxygen (C/O) spectroscopy, the system features an array of three gamma-detectors (referenced as Near, Far and Long) for increased sensitivity to gas and porosity. One of the initial applications of this system was reservoir monitoring of a CO_2 flood in the Permian Basin of west Texas.

The Goldsmith-Landreth (San Andres) field of Ector County, Texas was initially discovered in the 1930's. After initial production, the field went through years of water-flooding and by the mid 1980's the reservoir was at residual oil saturation. In 2009, Legado Resources began a pilot study on recovering the residual oil by CO_2 flooding. In contrast to gravity-drained miscible flooding, the pilot used a more active flooding in addition to water-flooding to produce the residual oil. This flood also targeted the residual oil below the ancient oil-water contact. The RAS system was used for monitoring CO_2 position and movement, as well as defining the base of the residual oil. This San Andres reservoir is a dolomite reservoir with porosities in the range 6 to 16 percent; the produced water is also the injection water and is in the range 40 Kppm to 50 Kppm sodium chlorides. A quick-look processing recipe was applied using the ratios of the Near and Long detectors to estimate porosity and gas-in-place. Sections of the reservoir with gas-in-place were assigned an *ad hoc* gas saturation based on literature for west Texas CO_2 floods; the parameters of Sigma-based oil saturation and the porosity calculations were matched to core data.

In an effort to measure gas saturation more accurately, a follow-up project with detailed Monte Carlo models that included the specifics on reservoir rocks and fluids were built and processed. In the literature, (Odom 2001, Trcka 2006, Zett 2011) are discussions on using the multi-detector pulsed-neutron (MDPN) data to measure gas saturation independently using the long-spaced response. Given an independent measurement of the gas saturation, in reservoirs with saline formation water, the Sigma interpretation can be used for oil/water saturation. In contrast, previous literature on 3-phase monitoring of floods (Badruzzaman 1998, Harness 1998, Zalan 2004) describes using carbon-oxygen and sigma as the two inputs in a 3-phase fluid solution. These techniques were primarily focused on steam-floods with fresh water, thus sigma drove the gas (steam) saturation and C/O drove the oil saturation. The SIGMA-MDPN recipe is more robust than the SIGMA-C/O model and can be logged in a single logging pass, however, care must be exercised in diagnosing wellbore uncertainty. Several examples of the interpretation are presented, along with borehole diagnostics from the RAS and cement bond logs.

INTRODUCTION

The Goldsmith-Landreth San Andres Unit (GLSAU) is a hydrocarbon reservoir in the Permian Basin of west Texas (see location Map, Figure 1). The reservoir is sealed by low-porosity, low-permeability, peritidal dolomitic wackestones and packstones with included anhydrite (see Figure 2). The reservoir facies are predominately dolomitic wackestones and fusilinid packstones with some traces of anhydrite and gypsum. Development of the field began in the 1940's and by the 1960's the field was unitized and secondary water-flooding was used for production until the 1980's when production dropped to un-economic levels. Below the oil-water contact in the Main Pay Zone (MPZ) is an ancient oil-water contact and there is residual oil in place. So, as well as the residual oil left after years of water-flooding in the MPZ, the oil in this Residual Oil Zone (ROZ) is the also a target of enhanced recovery by carbon-dioxide flooding. Figure 3 charts the modern day oil saturation from core data, we note that the efficiency of water-flooding by operators is similar to the water flooding by nature; the oil saturations in the MPZ and the ROZ are very similar.

Gravity-stable CO_2 floods have been operational in the Permian basins for several decades (Schneider 1996) where carbon dioxide is injected to build a gas cap; the miscible oil is pushed down and harvested. In the GLSAU reservoir a more active approach to the flooding was adopted. As the carbon dioxide is injected in the reservoir it becomes entrained in the oil. This miscible oil phase has a larger volume and lower viscosity and thus a portion of it is washed along with the flood to a producer well. It is important to understand these reservoir dynamics to devise an analysis program. In this case we may see some moved oil in zones that may have higher oil saturation, but in most of the flushed zones (and virgin zones) the oil saturation will only change a few percent, so the analysis objective is focused on carbon dioxide placement and saturation.

Pulsed-neutron systems were designed for monitoring conventional reservoirs and reservoir fluids (e.g. oil, salt-water, hydrocarbon gas) by nuclear reactions with elements such as hydrogen, oxygen, and carbon. The analysis has been extended to three-phase saturations in steam floods (Badruzzaman 1998, Harness 1998, Zalan 2004) by utilizing Pulsed Neutron Capture (PNC, Sigma logging) for steam versus liquids and Pulsed Neutron Spectroscopy (PNS, Carbon/Oxygen logging) for oil versus water. Carbon dioxide as a third fluid phase poses some special concerns for three-phase analysis. At the GLSAU reservoir depth and temperature the CO2 has a density of 0.77 g/cc and it is a fluid that moves in the reservoir similar to gas by displacing the water. PNC measurements respond to the lack of hydrogen, the displaced salt water and the very low capture cross-section of carbon dioxide. For PNS, the response is ambiguous in measuring CO_2 saturation versus water saturation (i.e. CO_2 versus H_2O). Quinlan, et al., (2012) have proposed using just the carbon yield in a three-phase solution to map to CO_2 saturation, but in general the statistics and uncertainty of C/O logging pose some practical limits when applied to low porosity reservoirs like GLSAU. Carbon-oxygen logging has been applied to carbon dioxide floods such as the Wellman Reef (Schneider (1996)) and Reinecke Field (Odom 2000) in a qualitative sense to target the moved oil. In these wells, the hydrogen excavation effect (i.e. comparing total porosity to neutron porosity) was exploited to map gas-in-place.

Over the past 20 years, techniques for extracting formation density from pulsed-neutron measurements have been discussed in the literature. In the late 1990's, the optimization of the PN density measurement was studied (Odom 2001b) and the long-spacing was shown to have increased sensitivity. Based on this work a prototype was tested with a long-spacing (Odom 2001a). Accurate PN density measurements are impacted by wellbore and formation uncertainty, so, relative techniques were developed to directly measure gas saturation (Trcka 2006, Inanc 2009, Zett 2012a, Zett 2012b) using Multi-Detector Pulsed-Neutron (MDPN) instruments. These methods utilize the ratio of near-spaced to long-spaced counts in the neutron pulse period compared to the ratio of near-spaced to long-spaced counts during the capture time to solve for gas saturation.

For the GLSAU reservoir, most wells do not have open-hole logs, so the challenge is to measure porosity and CO_2 saturation. The Reservoir Analysis System (RAS) introduced by Allied Wireline and Hunter Well Science uses an array of three detectors as shown in Figure 4. As a first step, a quick-look analysis was developed using 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, wellbores and RAS construction are inputs to the neutron-photon transport code MCNP (Briesmeister, (1993)). The computer-based models generate data sets for solving the inverse problem and the spatial response of the detector array is mapped to estimates of porosity and carbon dioxide saturation. After solving for total porosity and gas saturation (S_g), the Sigma S_w is solved for all three fluids. Given the low porosity, three reservoir fluids, and water salinity uncertainty, the Sigma water saturation (S_w) results are semi-quantitative. Even with error bars, the S_w calculations can cross-check gas-in-place and define the base of the residual oil zone (ROZ).

There are aspects of the GLSAU reservoir that help refine the analysis accuracy for carbon dioxide saturation and porosity.

- Figure 5 is a multi-mineral analysis of the open-hole logs that was tied to core analysis for an offset well. We note that the rock make-up 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; the miscible phases can be broken into CO_2 and original oil for the analysis. Thus, estimates of CO_2 saturation should be independent of oil saturation.
- Wells in the GLSAU reservoir have very good cement jobs, this combined with the fast transit times in dolomite yield a potent analysis of the wellbore condition.

RAS SYSTEM DESCRIPTION

The Hunter Well Science RAS is a multi-detector pulsed-neutron system for measuring reservoir fluid saturation using Sigma and Carbon-Oxygen techniques. For the GLSAU analysis, the system was operated in the Sigma logging mode diagrammed in Figure 4. In this mode the neutron pulse is 200 microseconds and the decay data is collected in 19 time bins for each detector. The sonde has three gamma detectors, referenced as Near, Far and Long, the detector array as diagrammed in Figure 4.

QUICK-LOOK OVERLAY

The Near to Long Capture ratio is referenced RNLC and the Near to Long ratio during the neutron burst is referenced RNLB. To set up the quick look overlay of Figure 6, the first step is to normalize RNLC and RNLB in the water filled zones below ROZ to the zero porosity in the caprock. The overlay of RNLC and RNLB is plotted in track one of the plot, with gas-shading when RNLC is less than RNLB. Also in track one is the SIGMA measurement. In track two of the plot is SW_SIGMA_GAS, the water saturation from sigma using two fluids, a mixture of oil and carbon dioxide versus salt water. In the third track are bulk volumes using PHIN_RAS, the RAS neutron porosity as the effective porosity. Where the RNLC-RNLB overlay and sigma indicate gas-in-place, the bulk volume of carbon dioxide is assigned and *ad hoc* value based on typical saturations. From the plot we 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. As stated above, the cement quality in the GLSAU reservoir is very good, but there is still an uncertainty on borehole size. Previous modeling on wellbore uncertainty (Odom 1999), and practical analysis suggest that cement has a presentation similar to shale (high hydrogen, high oxygen) for pulsed-neutron measurements. Thus, enlarged hole-size will cause the porosity to read too high and the gas saturation to read too low. It is rational that the third detector will have deeper penetration, but we would expect a similar shale-like response for thicker cement sheaths.

The good cement quality and fast dolomite formations allow imaging of the formation arrival in the cement bond log data. In Figure 7, the quick-look analysis is checked by noting the cement bond log. Given a maximum travel time for the dolomite (e.g. 60 microseconds/foot) and the bit-size we can set a bad-hole flag for sections with enlarged wellbores. As noted, the variable density log (5-foot receiver VDL) of the interval indicates an enlarged wellbore. Also one zone appears fractured; the chevrons in the VDL suggest that these are conductive fractures (Hornby 1999).

SOLVING FOR GAS SATURATION (S_G) AND POROSITY

To map the RAS measurements into gas saturation and porosity, the computer code MCNP (Briesmeister, (1993)) was used to model the tool response. Use of this code is widely described in the literature for modeling nuclear tool response. For this study, computer experiments were designed for a dolomite reservoir with a wellbore of 8.75-inch and 7-inch (23 lb) casing, well cemented and centralized. The fluids modeled were: oil, CO_2 at 0.77 g/cc, and salt water (50 Kppm NaCl).

Figure 8 diagrams the modeled data for RNLC, the near-to-far capture ratio. Figure 9 diagrams the modeled data for RNLB, the near-to-far ratio during the neutron pulse; both response fans show sensitivity to porosity and CO_2

saturation. In comparing the fans we note what was observed on the quick-look overlay; both have similar porosity response, but the RNLC has a larger sensitivity to gas (i.e. drops further in normalized overlay). With the computer models, a sufficient number of particles are sampled to get results that are statistically useful. With the logging tool this relates to logging speed and precision. For the GLSAU analysis, the RAS system was logged at 12 feet per minute, the measurement precision results were:

- RNLC average deviation = 0.208
- RNLB average deviation = .122
- RAS neutron porosity precision is +/- 0.6 porosity units (p.u.) in the range 0 to 18 p.u.

To simultaneously solve for porosity and CO_2 saturation from RNLC and RNLB response is problematic, because the responses are similar. Figure 10 is a cross-plot of RNLB and RNLC for the modeled data; we note that the parametric differences in the solution have a similar vector. The figure shows the change in porosity from 12% to 6 %, and the change in gas saturation for 12% porosity from S_g = 0 to S_g = 40%. To transform the data set for more independent parameters, let's dig deeper. The difference in the ratios RNLB and RNLC can be linked to gamma rays from inelastic scattering that are only present during the neutron pulse (i.e. RNLB). Typically, inelastic gammas are resolved in carbon-oxygen logging, but the inelastic gammas can be stripped from the wider pulse widths using techniques described in Odom (1994) and Neuman (1999). 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 to RNLB; the precision of RNLI is 0.62 average deviation. The cross-plot of RNLI and the RAS total porosity PHIRT is shown Figure 11; the Z-axis colors are based on SIGMA. The response fan is superposed on the cross-plot, given the average deviation of RNLI seen in the well; the precision of the CO_2 saturation at 12 p.u. is 12 saturation units.

Well data processed for the RAS total porosity (PHIRT); in Figure 12 the RAS total porosity is compared to total porosity from open-hole neutron-density porosity. To get the tight correlation with open-hole seen in the figure, the PHIRT was boosted by 1.5 p.u., (note: there was no basis for this adjustment other than regression to the mean of open-hole).

To reduce the variables for the Sigma S_w calculation, the total porosity (PHIRT) and the CO_2 saturation (SGAS) are used to calculate an "excavated" porosity, where:

PHIRTX = PHIRT * (1 – SGAS)

In this manner the volume of the carbon dioxide 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 we add salinity uncertainty, the S_w results are semi-quantitative, but are still useful for determining levels in the wells such as the base of the ROZ.

ANALYSIS EXAMPLES

The analysis of one of the wells is shown in Figure 13, the curves shown are:

Track 1: Correlation
  GR – natural gamma ray
Track 2: Quick-look overlay
  SIGMA – Sigma
  RNLB Overlay – Ratio Near to Long Burst
  RNLC Overlay – RNLC normalized to RNLB
Track 3: Porosity
  PHIRT – RAS Total porosity
  PHINWT – RAS Neutron porosity
Track 4: Fluids

SGAS – CO_2 Saturation
SW SIGMA OIL – S_w from Sigma and PHIRTX solved for oil versus salt-water
Track 5: Bulk volumes
PHIRT – RAS Total porosity
BVW – Bulk Volume water
BVL – Bulk Volume Liquids

The ROZ and MPZ 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, the higher gas saturations in this section is the original gas cap.

In the second example, a cross-section of three wells on a north-south line is plotted in Figure 14. The cross-section has been stratigraphically flattened by correlation of facies near the top of the reservoir. These wells are separated by rows of injection wells. By correlation of injection profiles (in the injection wells) and RAS 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.

CONCLUSIONS

In the GLSAU analysis the multi-detector pulsed-neutron measurements are used to derive total porosity and gas saturation from the detector array data. The basic reservoir description was provided from core data and open-hole logging. The pulsed-neutron logging provided real-time analysis of carbon dioxide placement in the reservoir flood with much higher well density coverage.

Inherent in cased reservoir analysis is wellbore uncertainty; it is important to use tools and information such as cement bond logs, drilling history, etc. to qualify the results.

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REFERENCES

Badruzzaman, A., Skillin, R.H., Zalan, T.A., Badruzzaman, T., Nhuyen, .T., : (1998), “Accurate oil saturation determination using carborn/oxygen logs in three-phase reservoirs” Presented at the 1998 SPWLA Annual Symposium, Keystone,Colorado. Paper: CC

Briesmeister, J.F., (Ed.),: (1993) “MCNP-A General Monte Carlo N-Particle Transport Code,” Los Alamos Report, LA- 12625-M.

Harness, P., Shotts, N., Hemingway, J., Rose, D., van der Sluis, R.: (1998) “Accurate oil saturation determination and monitoring in a heavy oil reservoir” Presented at the 1998 SPE Western Regional Meeting, Bakersfield, California.

Hornby, B.B., Lorsong, J.A., Wydrinski, R., Vittachi, A.R.: (1999), “Integrated fracture analysis using borehole geophysical techniques” Presented at the 1999 SPWLA Annual Symposium in Olso,Norway.SPE paper 59717

Inanc, F., Gilchrist, W.A., Ansari, R. and Chace, D.: (2009) “Physical Basis, Modeling and Interpretation of a New Gas Saturation Measurement for Cased Wells” Presented at the 2009 SPWLA Annual Logging Symposium in the Woodlands, Texas

Neuman, C.H., Sullivan, M.J. and Belanger, D.L.,: (1999) “An Investigation of Density Derived from Pulsed Neutron Capture Measurements” Presented at the 1999 Annual Technical Conference and Exhibition in Houston, Texas SPE 56647

Odom, R.C.: “Pulsed-neutron decay tool for measuring gamma radiation energy spectra for fast neutron inelastic collisions and thermal neutron capture events,” United States Patent 5,374,823 issued December 20,1994.

Odom, R.C., Bailey, S.M., Wilson, R.D., Archer, M.P.: (1999) “Pulsed neutron density measurements: Modeling the depth of investigation and cased-hole wellbore uncertainties” Presented at 1999 SPWLA Annual Symposium in Oslo, Norway Paper JJ

Odom, R.C., Hogan, P., and Rogers, C., Steckel, M.F.,: (2000) “A Pulsed Neutron Analysis Model for Carbon Dioxide Floods: Applications Reinecke Field, West Texas” Presented at the 2000 SPE Permain Basin Oil and Gas Recovery in Midland, Texas. Paper SPE 59717

Odom, R.C., Wilson, R.D., Ladtkow, R.K.,: (2001a) “Log examples with a prototype three-detector pulsed-neutron system for measurement of cased-hole neutron and density porosities” Presented at the 2001 SPE Rocky Mountain Petroleum Technology Conference in Keystone, Colorado. Paper SPE 71042

Odom, R.C., Tiller, D.E., Wilson, R.D.,: (2001b) “Improvements in a through-casing pulsed-neutron density log” Presented at the 2001 Annual Technician Conference in New Orleans, Louisiana. Paper SPE 71742

Pickett, A.,: (2011) “Goldsmith-Landreth Unit, Other ROZ CO_2 EOR Projects Give Legacy Fields New Life” American Oil and Gas Reporter, June 2011

Quinian, T., Sibbit, A., Rose, D., Brahmakulam, J., Zhou, T., Fitzgerald, J., Kimminaum, S.,: (2012) “Evaluation of the Carbon Dioxide Response on Pulsed Neutron Logs” Presented at the 2012 SPE Annual Technician Conference and Exhibition in San Antonio, Texas. Paper SPE 159448

Schneider, B.D., Hogan II, G.P., Holt Jr., W.N.: (1996), “Using pulsed neutron decay-spectrum data and multi-inflatable packer plugdown assemblies improve oil production rates in a mature CO_2 flood,” Presented at the 1996 SPE Permian Basin Oil & Gas Recovery Conference in Midland, Texas. Paper SPE 35165

Trcka, D., Gilchrist, A., Riley, S., Bruner, M., Esfandiari, T., Ly, T., Shearin, D., Patino, T., Murray, H., Potter, J., Rose, R., Chen, J., Olsen, S., Lovera, O., McCants, D., Berger. A., Ellsworth, K., Barolak, G., Martain, R., McFall, A., Guo, P.: (2006), “Field trials of a new method for measurement of formation gas using pulsed-neutron instrumentation,” Presented at the 2006 SPE Annual Technical Conference and Exhibition in San Antonio, Texas. SPE Paper 102350

Zalan, T.A., Badruzzaman, A., Harness, P.E.: (2004) “Methodologies and applications of calculating steam saturations in cased hole,” Presented at the 2004 SPWLA Annual Symposium in Noordwijk, Netherlands. Paper H

Zett, A., Webster, M., Rose, H., Riley, S., Trcka, D., Kadam, N.,: (2012a) “Surveillance of Complex Displacement Mechanisms in Mature Reservoirs to Maximize Recovery” Presented at the 2012 SPE Annual Technician Conference and Exhibition in San Antonio, Texas SPE 159185

Zett, A., Webster, M., Spain, D., Surles, D., Colbert, C,.: (2012b) “Application of New Generation Multi Detector Pulsed Neutron Technology in Petrophysical Surveillance” Presented at the 2012 SPWLA 53rd Annual Logging Symposium in Cartagena, Columbia

FIGURES

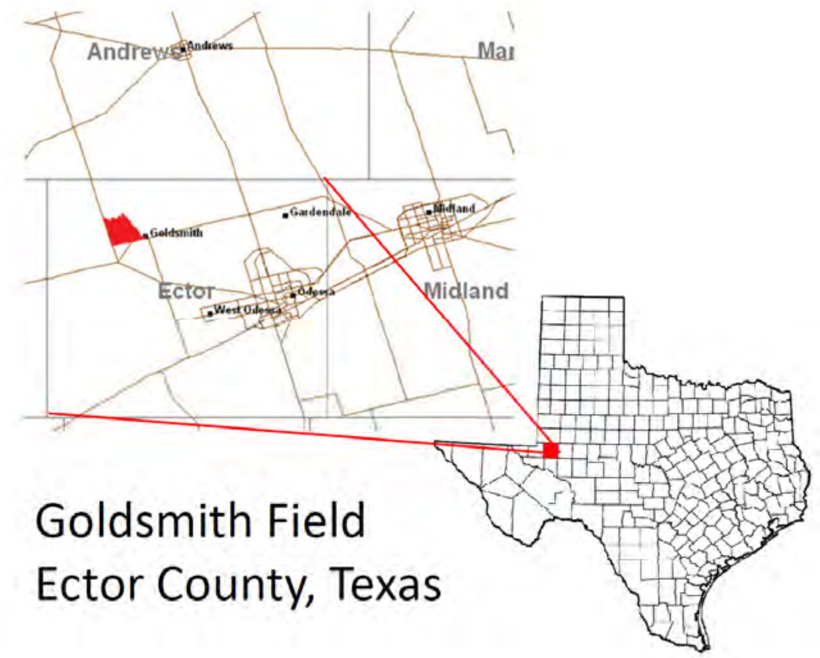

Figure 1. Location Map of Goldsmith-Landreth San Andres Unit (GLSAU)

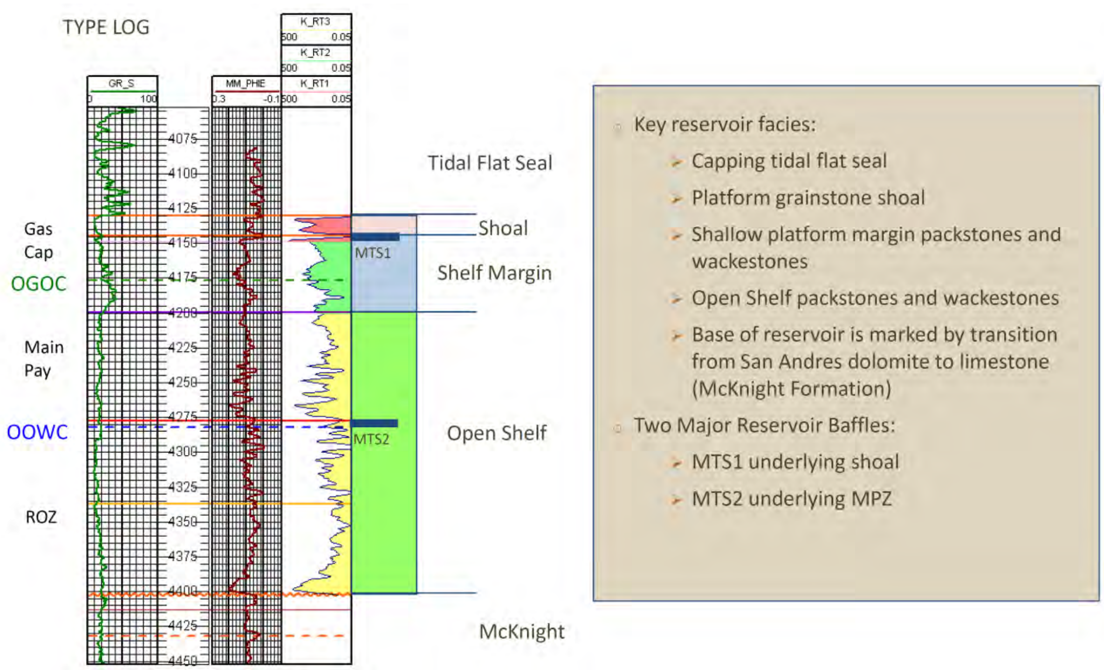

Figure 2. Type Log and Stratagraphic column in Goldsmith-Landreth San Andres Unit.

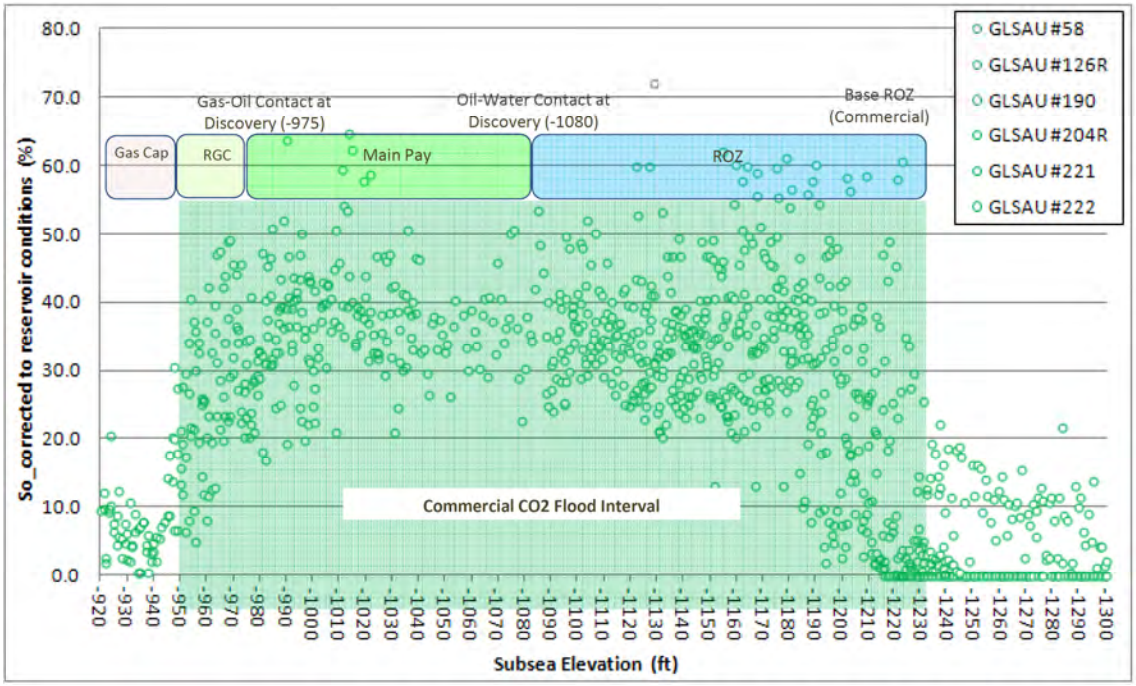

Figure 3. Core analysis before the CO2 flooding shows that the oil saturation in the Main Pay Zone (MPZ) and the Residual Oil Zone (ROZ) is very similar.

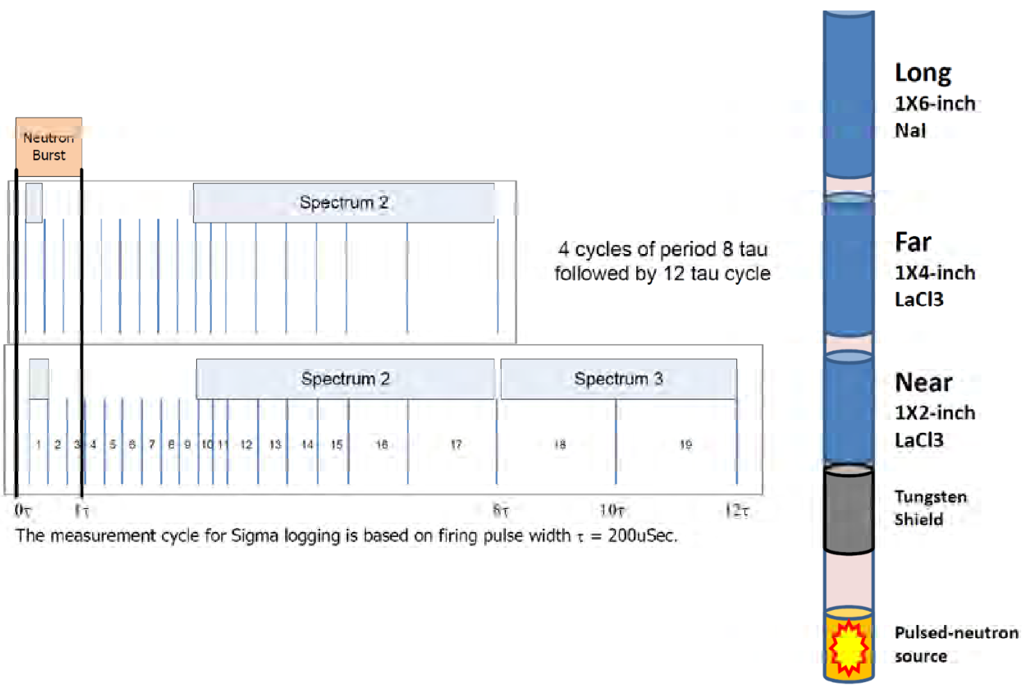

Figure 4. The RAS Sigma Mode was used for the analysis. This mode has a 200 microsecond neutron pulse width and 19 time bins sample the gamma ray counts in the detector array. The RAS detector array utilizes three gamma ray detectors, referenced Near, Far and Long.

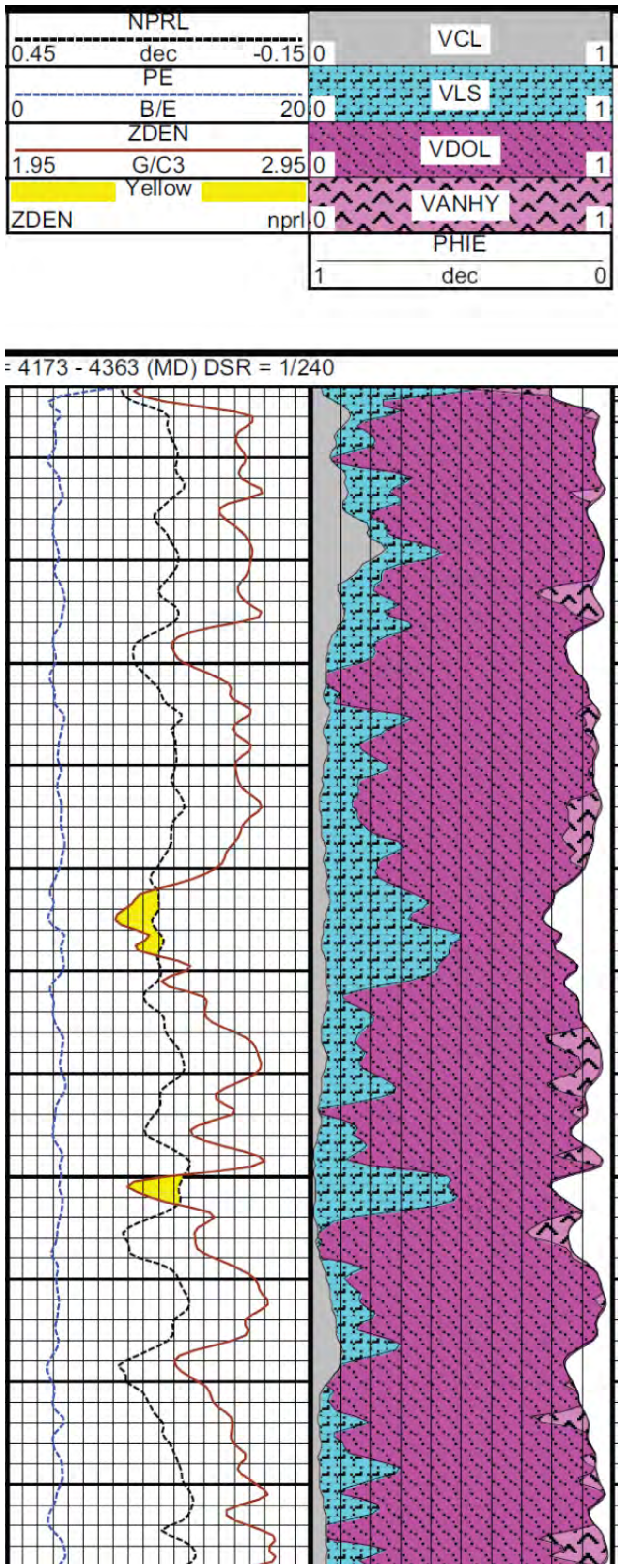

Figure 5. Multi-Mineral Analysis of offset open-hole logs tied to core data. Reservoir is predominately Dolomite. Track one is the open-hole neutron porosity, density and photo-electric factor.

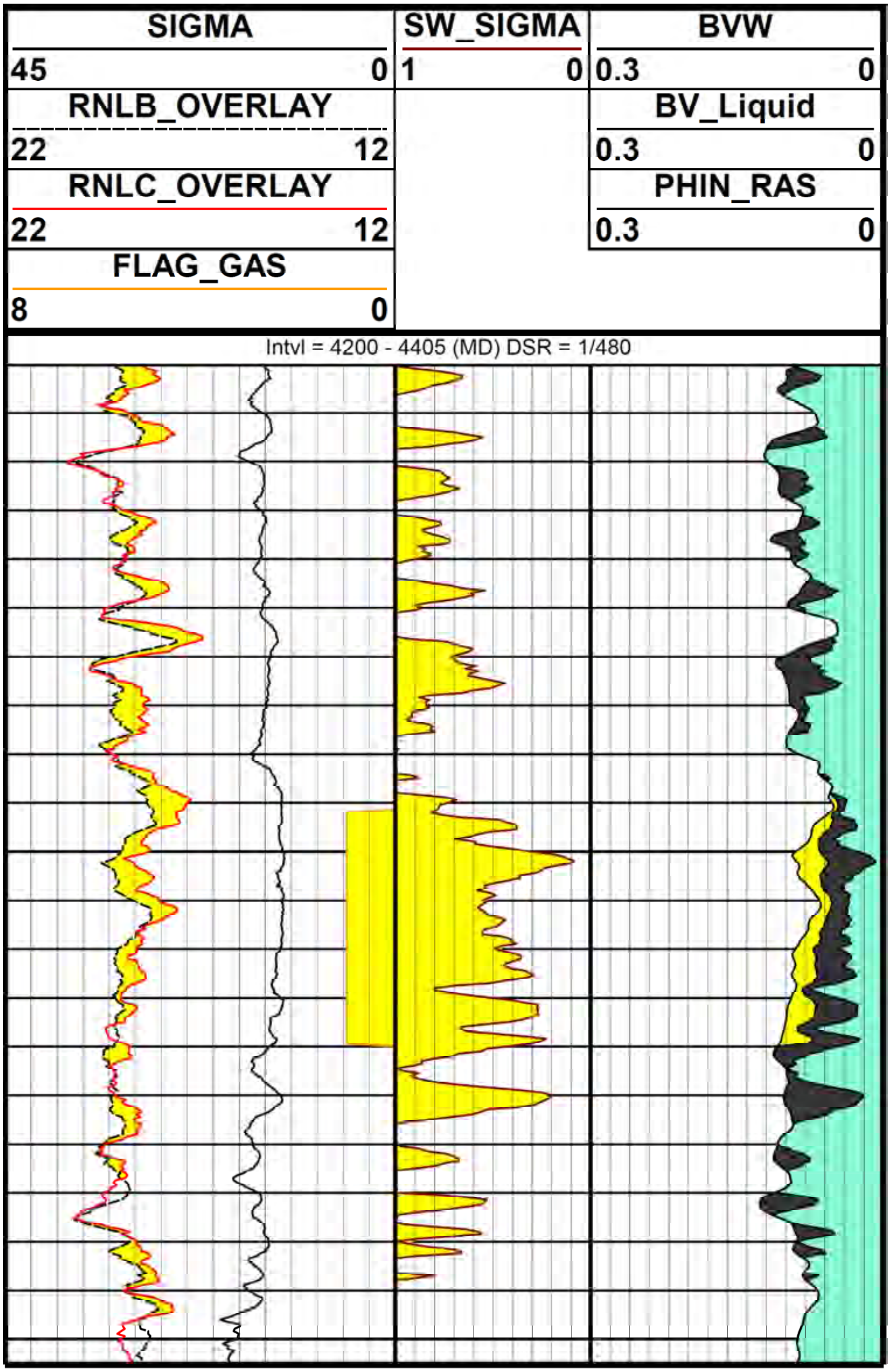

Figure 6. Quick-Look analysis of RAS data. The RNLC-RNLB overlay and Sigma response are used to flag gas-in-place. The neutron porosity from RAS is used as the effective porosity.

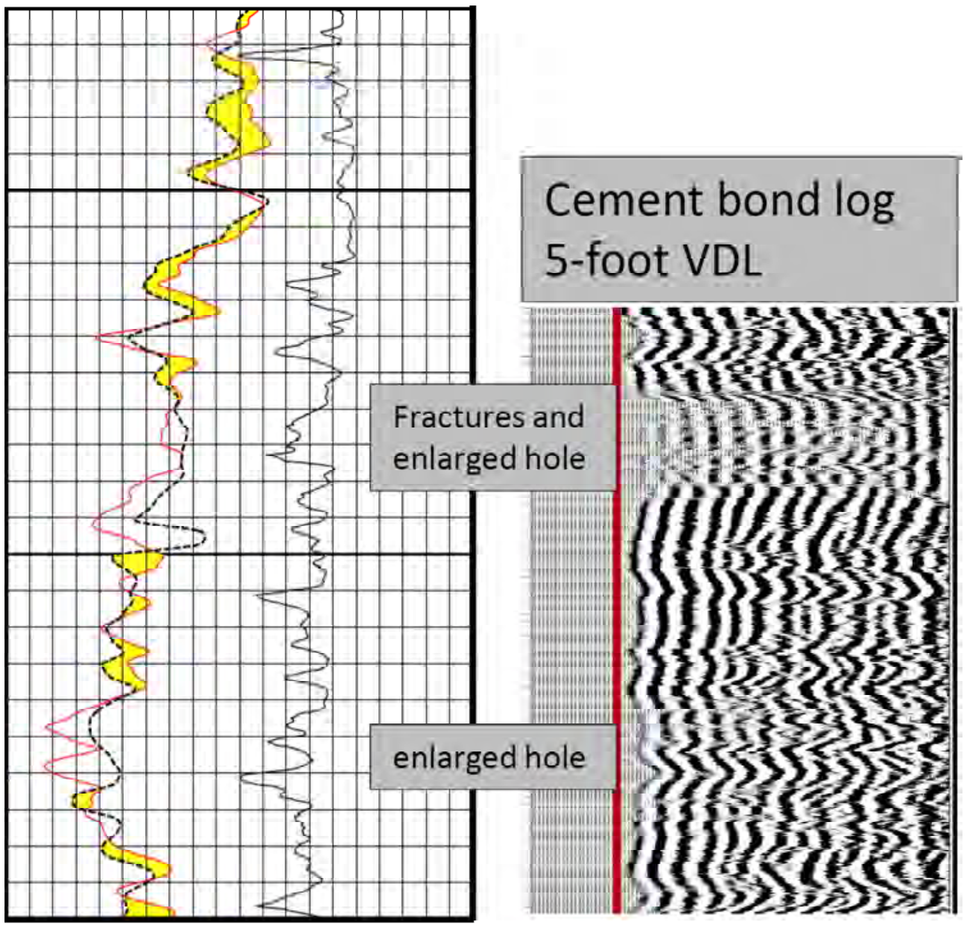

Figure 7. Inspection of the Cement Bond Log (CBL) is important to check the quality of the analysis.

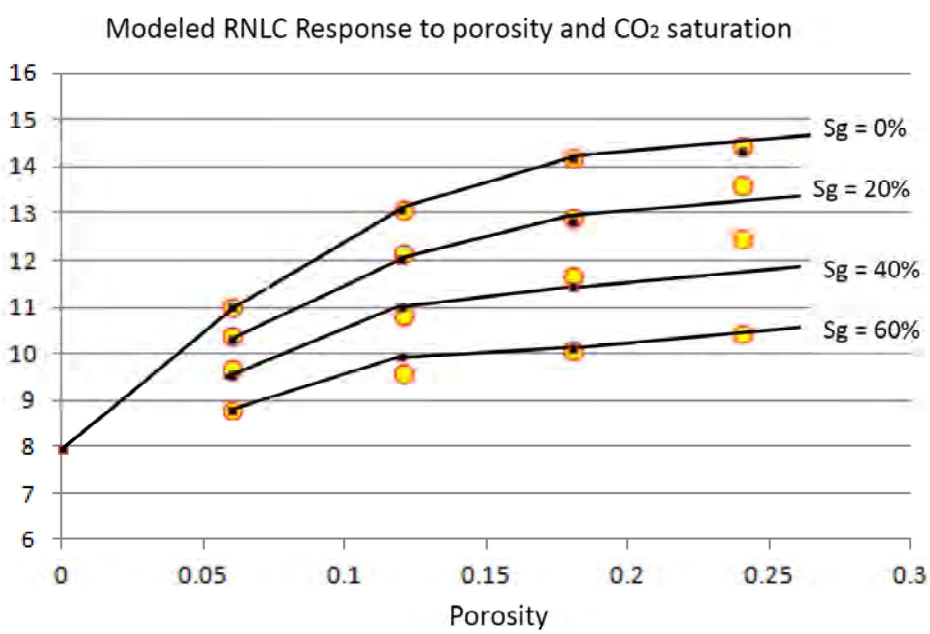

Figure 8. RNLC Response Model for porosity and CO_2 saturation from computer modeling

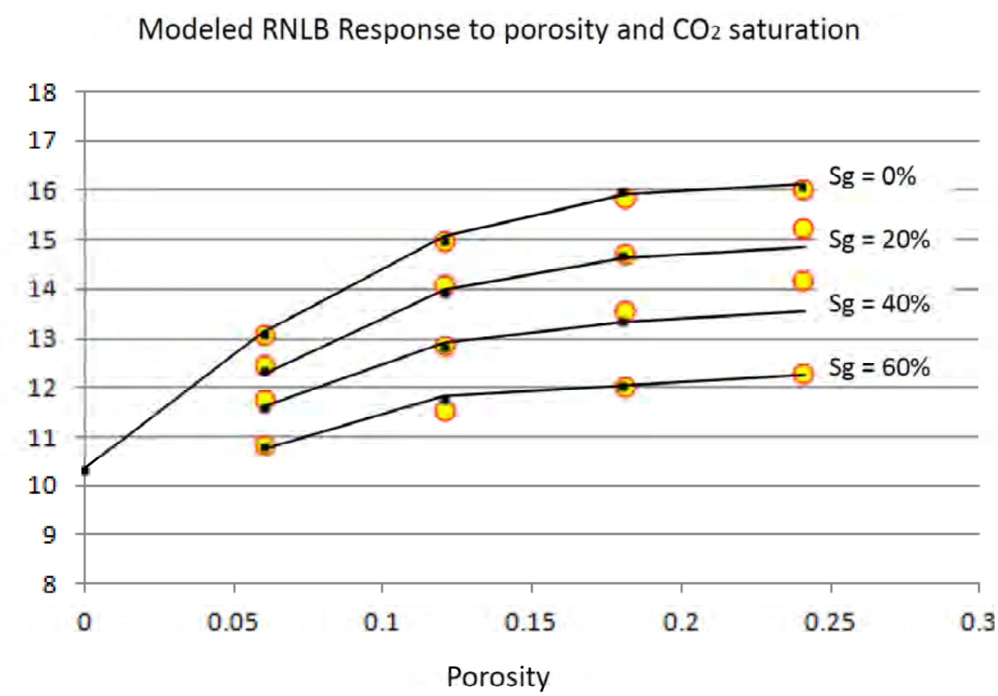

Figure 9. RNLB Response Model for porosity and CO_2 saturation from computer modeling

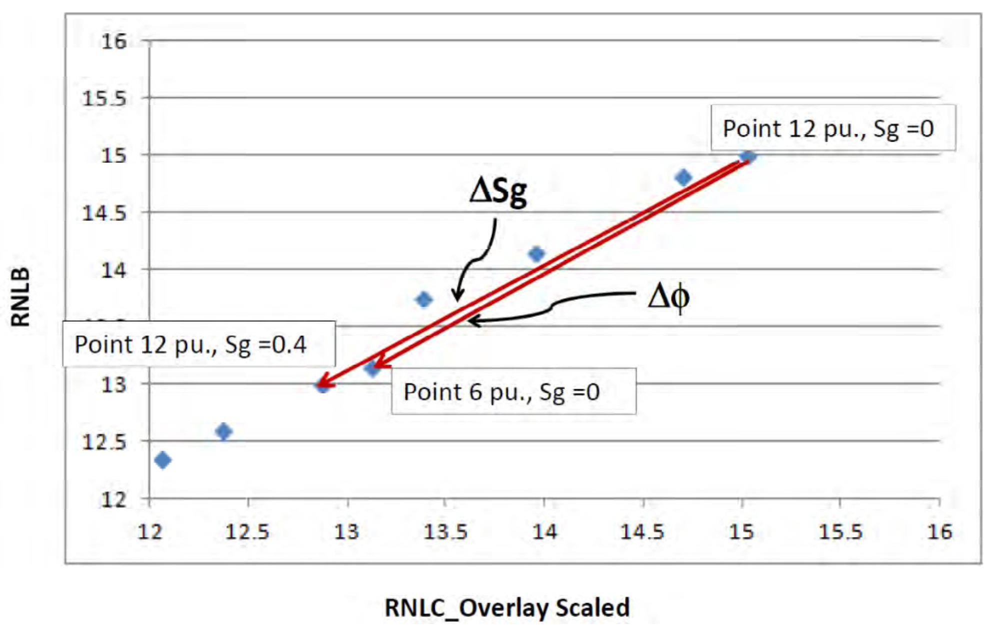

Figure 10. Cross-plot of RNLC and RNLB diagrams the change with respect to gas saturation and porosity, the similar difference vectors make a simultaneous solution problematic.

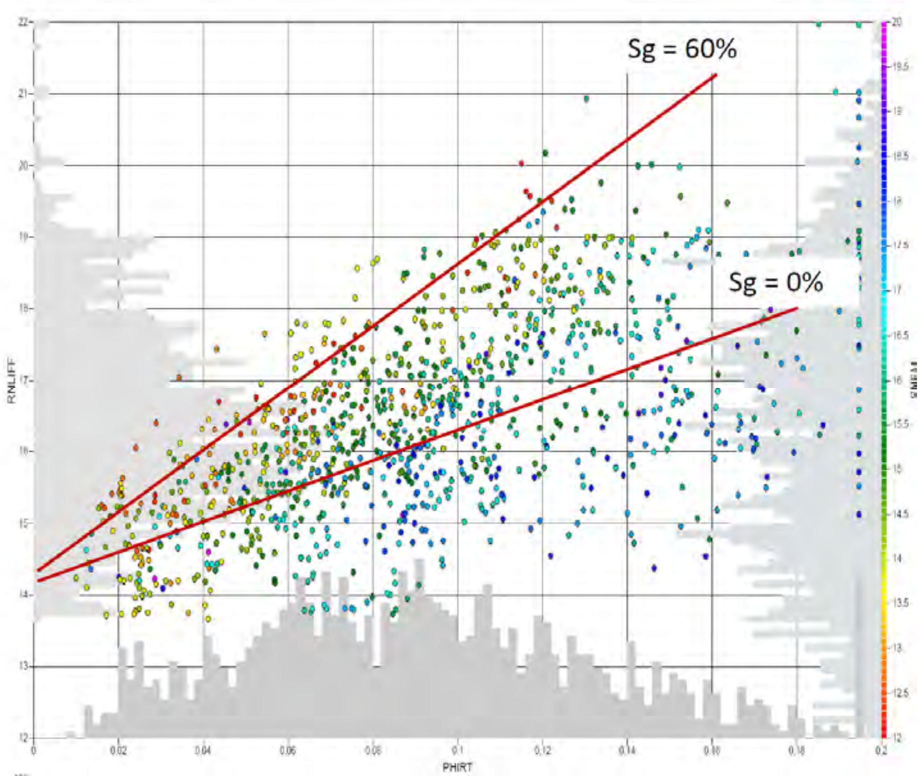

Figure 11. Cross-plot of RNLI versus RAS total porosity with Gas response fan superposed.

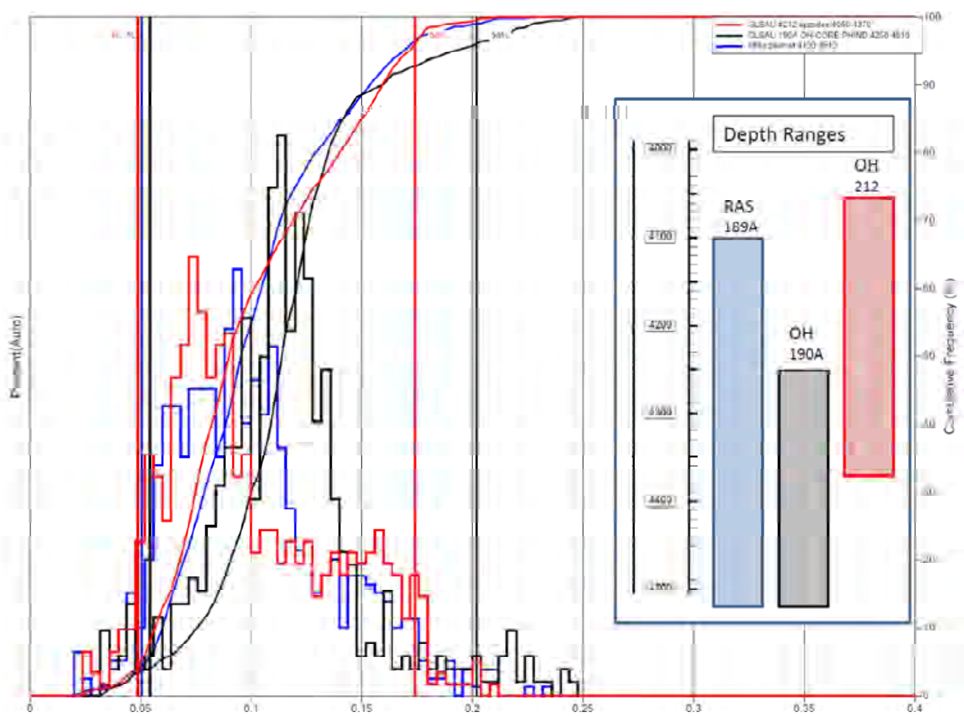

Figure 12. Comparison of RAS total porosity to open-hole total porosity in offset wells.

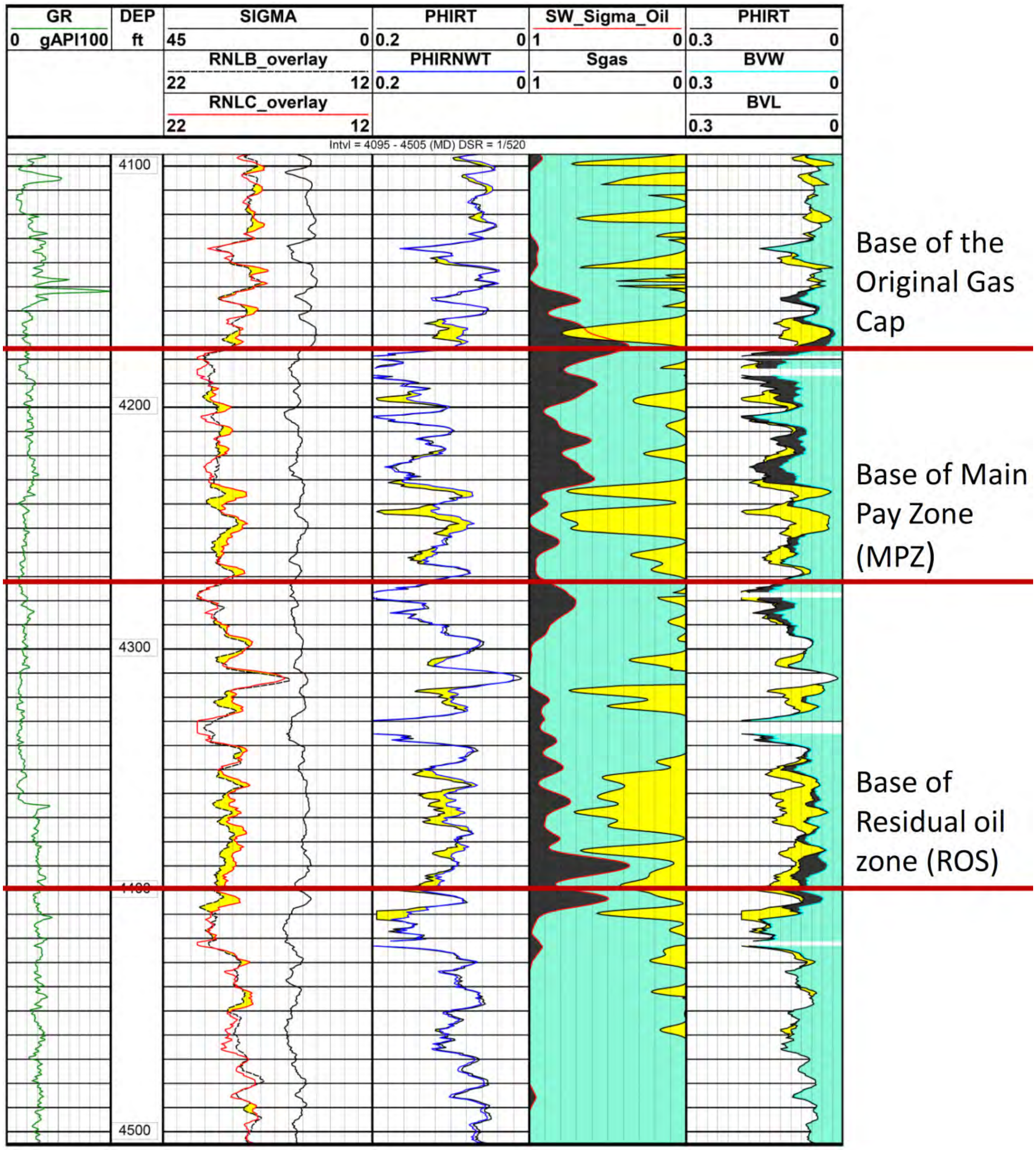

Figure 13. Plot of RAS analysis across the reservoir.

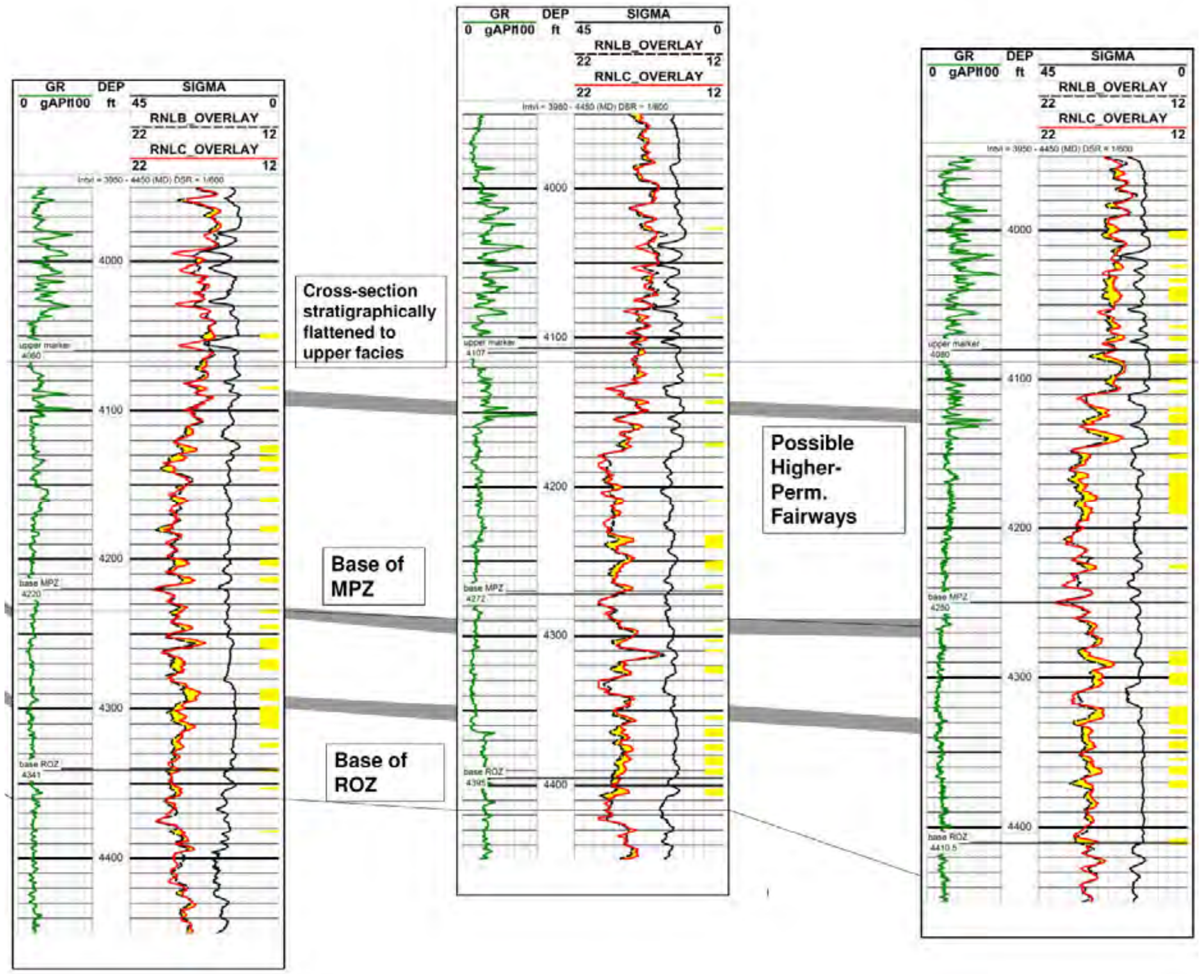

Figure 14. A North-to-South cross-section of three wells depth-flattened by correlation of upper facies. Each of these wells are separated by the rows of injection wells.