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Cased-Hole Formation Evaluation Using Advanced Multifunction Pulsed Neutron Measurement – Case Study from South of Iraq

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ABSTRACT

Efficient formation evaluation in heterogenous carbonate and clastic reservoirs is indispensable for estimating reserves and optimizing the testing and completion scheme of wells. E&P companies rely heavily on open-hole logs to acquire a wide spectrum of measurements necessary for this objective. Effective petrophysical analysis provide quantification of key formation elements including, but not limited to, mineralogy, porosity, reservoir fluids saturation and type, and rock permeability. Nonetheless, well-control issues can sometimes pose considerable limitations to measurement acquisition in open-hole leading to partial or complete compromise of data acquisition programs and subsequent loss of essential information. In such cases, acquiring alternative measurements specifically designed to work in cased-hole environment is the only mitigation strategy.
A widely known cased-hole logging solution is pulsed neutron measurements that have been introduced to the Oil and Gas industry decades ago. Recent advances in pulsed neutron tools technology greatly improve the quality of this type of cased-hole measurement and enrich the spectrum of its applications, bringing it closer to open-hole logs in terms of robustness. In the time domain, the measurement includes formation Sigma, for saturation in a saline environment, neutron thermal porosity (TPHI), and inelastic fast neutron cross section (FNXS) for gas identification. In the energy domain, the measurement includes Inelastic-Capture elemental yields for mineralogy and Total Organic Carbon (TOC), and Inelastic Carbon & Oxygen ratio for salinity-independent saturation estimation. These advanced measurements were deployed in one of the giant fields in the south of Iraq to compensate for the absence of open-hole logs by providing a comprehensive set of inputs for complete petrophysical analysis. The measurement was additionally implemented to evaluate the gravel pack integrity in a producer well that targeted clastic reservoirs where this type of completion is utilized. The study presents the results of this successful deployment and discusses the associated interpretation workflow that helped optimize the testing/completion design and characterize the reservoir fluids across different formations. The study will also discuss the workflow used for verifying the gravel pack integrity with the same measurement.

EXTENDED ABSTRACT

INTRODUCTION

Oil fields in south Iraq comprise of multiple carbonate and clastic reservoirs with varying petrophysical rock properties that require robust formation evaluation models to optimize testing & completion design and supplement static models. For the studied field, the characterization is reliant on open hole logs that are acquired across the target sections post-drilling. The open hole measurements are hence indispensable. However, well control issues can sometimes lead to logging cancellation to avoid further risks, as was the case in the investigated well in this study where high trip gases were continuously encountered across certain intervals which led to the decision of canceling open hole logging and casing the section directly. Cased hole pulsed neutron logging was hence considered to compensate for the missing information. Recent advances in this type of measurement had greatly enriched and improved the quality of the extracted outputs. The pulsed neutron measurement encompasses mineralogy quantification through inelastic and capture spectroscopy, porosity estimation (TPHI), and saturation evaluation. Saturation is evaluated through formation capture cross section (Sigma), and through the carbon-oxygen elemental ratios that are also evaluated during spectral analysis. The measurement additionally provides means for characterizing light oil and gas zones through the novel fast neutron cross-section measurement (FNXS) (Rose et al, 2015). This measurement enabled a comprehensive petrophysical evaluation of the studied well and fully compensated for the missing information from open-hole logging. The measurement was also utilized in a different scope in other wells in the same field to evaluate the gravel-pack integrity. Gravel-pack completion is utilized in some of the producer wells that target the shallow clastic reservoirs for the purpose of controlling sand production. The gravel-pack integrity can be impacted over time, and the pulsed neutron measurement provides a mean to verify the pack quality through a customized, spectroscopy-based workflow that was successfully implemented in this field too.

CASE-1 METHODOLOGY

The advanced pulsed neutron measurements were acquired in a well with absent open-hole logs, and a full processing & interpretation workflow was carried out to extract the required outputs, as described in Figure 1. The acquired data was first quality-checked for any inconsistencies or abnormal readings. Figure 2 shows excellent repeatability of the key logs between all the recorded passes with all quality-control indicators within tolerance. Advanced self-compensation algorithms implemented with these measurements greatly mitigate the impact of the environmental factor with limited user interference, producing unbiased, consistent outputs (Zhou et al 2018).

In the time domain, the cased-hole porosity (TPHI) was first verified against adjacent wells data and a very good match was observed with open-hole porosity, as illustrated in Figure 3. TPHI was next combined with formation Sigma and provided the salinity value of the formation water and other matrix parameters to compute water saturation using the following equation:

$$S_w = \frac{(\Sigma_{bulk} - \Sigma_{grain}) + \Phi * (\Sigma_{grain} - \Sigma_{HC})}{\Phi * (\Sigma_{water} - \Sigma_{HC})}$$

FNXS measurement was also corrected for environmental factors and calibrated against low porosity zones where no significant hydrocarbon impact is expected, as shown in Figure 4. In the energy domain, the inelastic and capture spectra are first decomposed into normalized elemental concentrations/yields after correcting for casing and completion contribution. Oxide closure is then applied to extract elemental and mineral dry weights, along with matrix properties. The spectroscopy processing workflow is described in Figure 5 (Radtke et al., 2012). Spectroscopy processing additionally provides the total carbon fraction (TC). Inorganic carbon (TIC), on the other hand, can be computed from the formation mineral components (such as calcite, dolomite…etc). Total organic carbon (TOC) can then be simply computed by subtracting TIC from TC, as illustrated in Figure 6. TOC is then transformed into hydrocarbon volume/saturation by incorporating porosity (TPHI) and hydrocarbon weight. Finally, the ratio of inelastic yields of C/O (carbon, representing hydrocarbon & oxygen, representing water) is also transformed into hydrocarbon saturation through a model-based transform that considers the completion, porosity, borehole holdup, and hydrocarbon properties. C/O and TOC-based saturations are independent of the borehole and formation water salinity and hence are important to investigate against the salinity-dependent Sigma saturation that can be impacted by changes in formation water properties due to injection or drilling fluid remnants.

CASE-1 RESULTS

The pulsed neutron analysis results for the studied well are presented in Figure 7 & Figure 8. The main target reservoir is deep carbonates, but the operator was still interested in evaluating porosity and lithology for the shallower clastic formations, as presented in Figure 7. The highly heterogenous mineralogy is evidently captured by the pulsed neutron measurements in this section, which could even be difficult to fully capture by standard open-hole logs. Figure 8 shows the evaluation results across the target carbonate formations. Clean, good porosity zones are identified from lithology results and TPHI porosity curve; saturation was then investigated against these zones. Sigma-based and C/O-based saturation (supported by TOC) were compared, and we could observe a contrasting profile in some of these intervals (indicated by black arrows in Figure 8). Sigma-based saturation was found to be influenced by fresh drilling mud filtrate (driving higher oil saturation) while C/O saturation was showing less oil against the same zones, possibly indicating higher oil mobility potential. These zones were suggested as candidate places for subsequent testing. Well test results ultimately confirmed a very high oil flow from these zones which were then selected for perforation. Additionally, FNXS confirmed the presence of a different, lighter hydrocarbon type toward the middle region of the carbonate section (highlighted by yellow shading in FNXS track); as opposed to the standard oil response observed on top and bottom layers.

CASE-2 METHODOLOGY

For the second case, the main scope was to evaluate the gravel pack integrity in wells with target clastic reservoirs. Gravel pack completion aids with sand control. Monitoring the condition of the pack with time is essential to avoid the adverse impact of sand production. Pulsed neutron measurement was deployed with the objective of verifying the gravel pack integrity and evaluating the remaining reservoir fluid saturations. (Olesen et al, 1989) showed the application of quantitative evaluation of the packing quality based on neutron activation of particular elements contained in the gravel pack material. The complete workflow described in Figure 1 was similarly implemented. The gravel pack assessment was carried out by evaluating the activation of the Silicon yield, which is the most sensitive measurement to the presence of quartz particles (which are typically the main constituents of the pack) using the following equation, which also involves iron yield:

$$Pack_{percentage} = \left(\frac{Measured(N1SI/(N1SI + N1FE)) - zero(N1SI/(N1SI + N1FE))}{good(N1SI/(N1SI + N1FE)) - zero(N1SI/(N1SI + N1FE))} \right) \times 100$$

The “good” and “zero” terms are calibration points that the interpreter will select after inspecting the investigated interval, while the “measured” term is the output of the spectroscopy analysis.

CASE-2 RESULTS

The pulsed neutron analysis results for gravel pack evaluation are presented in Figure 9. The estimated pack percentage shows a relatively uniform profile suggesting the acceptable condition of the pack across most of the interval with few depths that shows potential integrity issue as indicated by the lower values of the quality log. In a different scenario, the gravel could show more voids or less uniform profile, especially against the perforations where the flow happens.

CONCLUSION

Advanced pulsed neutron measurement provides a comprehensive, and wide spectrum of outputs that proved to be efficient and robust to compensate for the absence of open-hole logs. Also, these measurements can be used for a wide range of applications for the analysis behind casing, such as monitoring saturation levels and injection breakthrough, observing changes in formation salinity, gas detection, and gravel pack evaluation. However, interpretation of these cased hole measurements ideally requires deep expertise (particularly to integrate & assess various cased hole data types) and careful attention to the borehole environment, which can greatly influence the outcome of these analyses.

REFERENCES

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Rose, D., Zhou, T., Beekman, S., Quinlan, T., Delgadillo, M., Gonzalez, G. and Bailly, J.-P. (2015, August 10). An Innovative Slim Pulsed Neutron Logging Tool. Society of Petrophysicists and Well-Log Analysts.

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SUPPORTING FIGURES

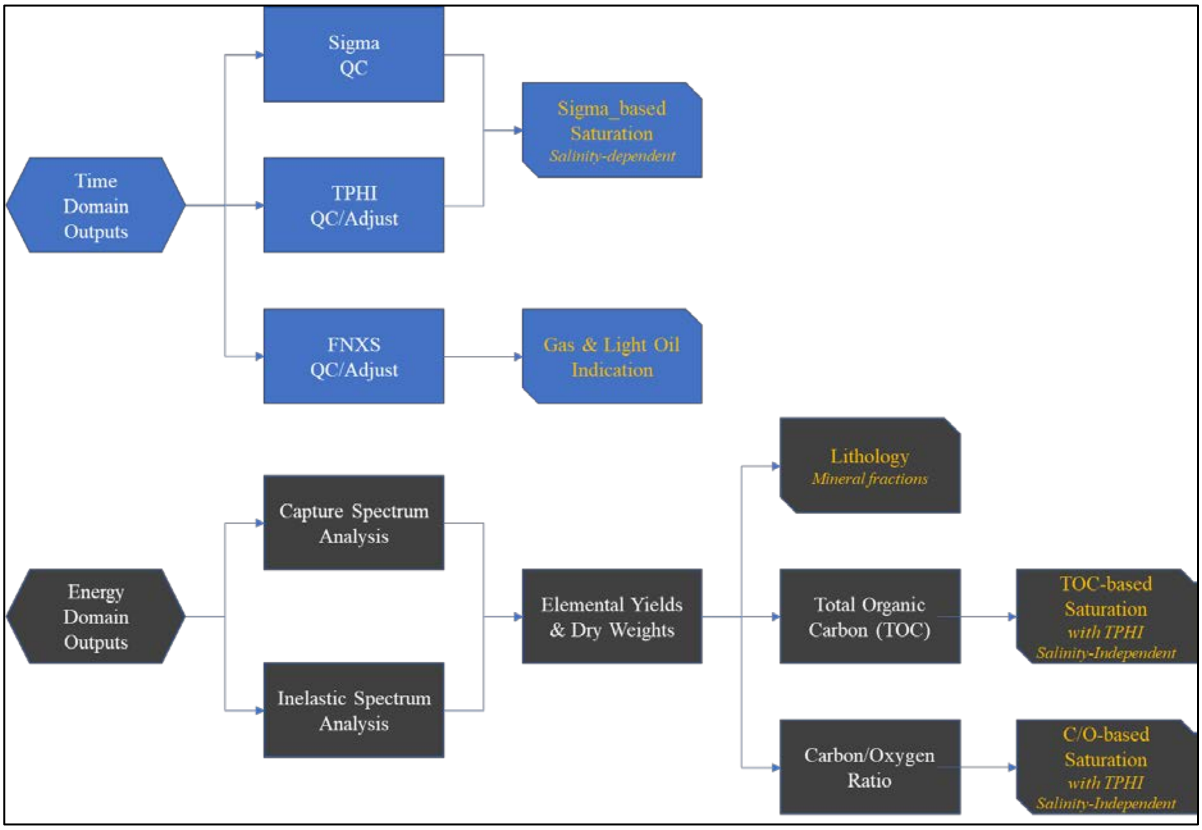

Figure 1: Summary of the extracted time-domain & energy-domain measurements, the final outputs are highlighted in orange colour.

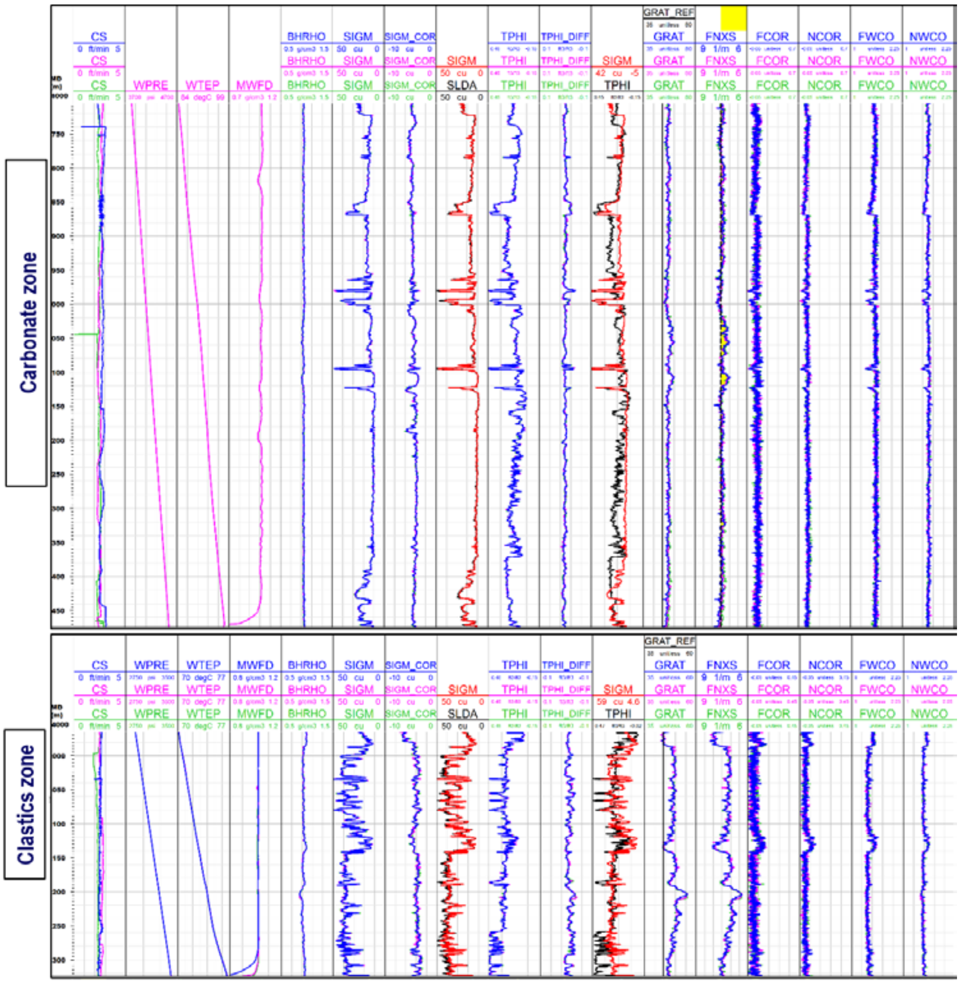

Figure 2. QC plot for the raw cased-hole Pulsed-Neutron measurements. Three acquisition passes were recorded (pass-1 in blue colour, pass-2 in pink colour, and pass-3 in green colour) with excellent repeatability.

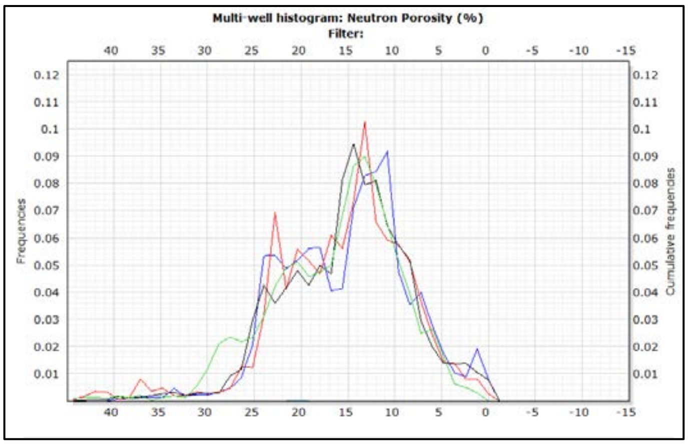

Figure 3. Histogram of cased-hole TPHI (in red colour) vs open-hole NPHI from adjacent wells.

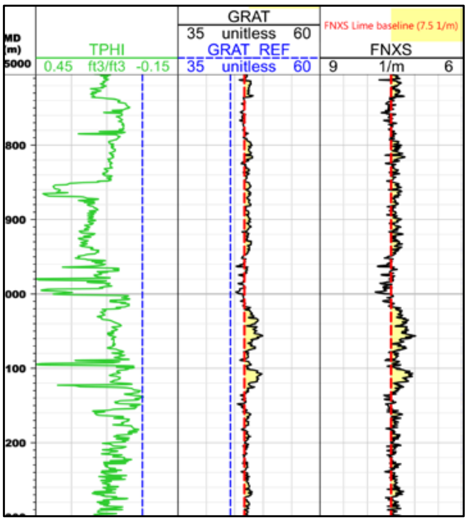

Figure 4. FNXS measurement environmental correction & calibration across the carbonate section.

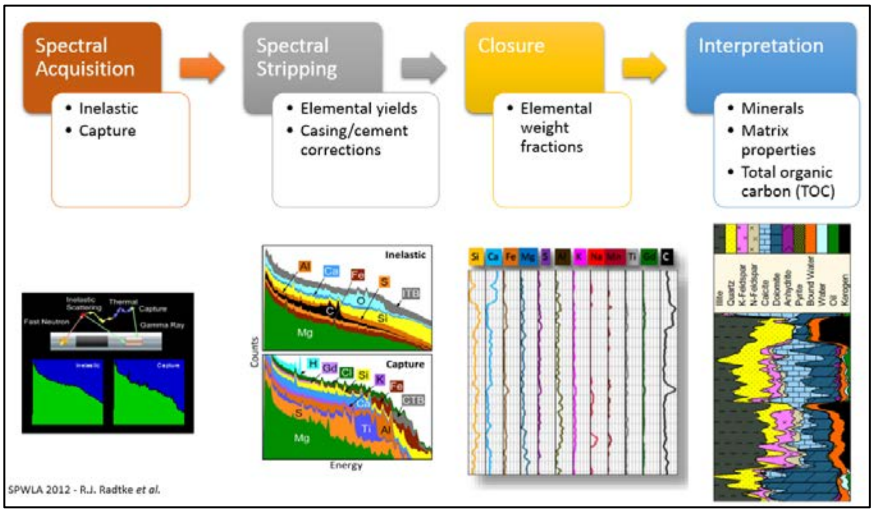

Figure 5. Pulsed-neutron spectroscopy processing workflow.

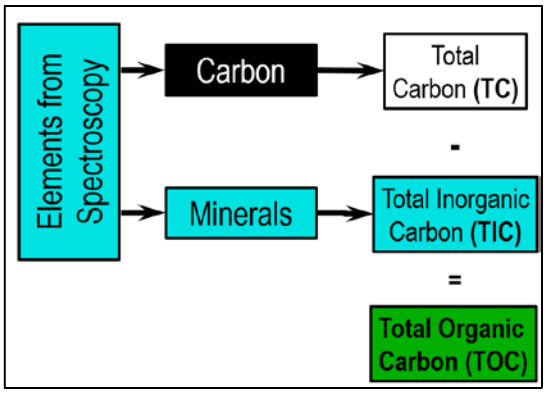

Figure 6. TOC computation from spectroscopy outputs.

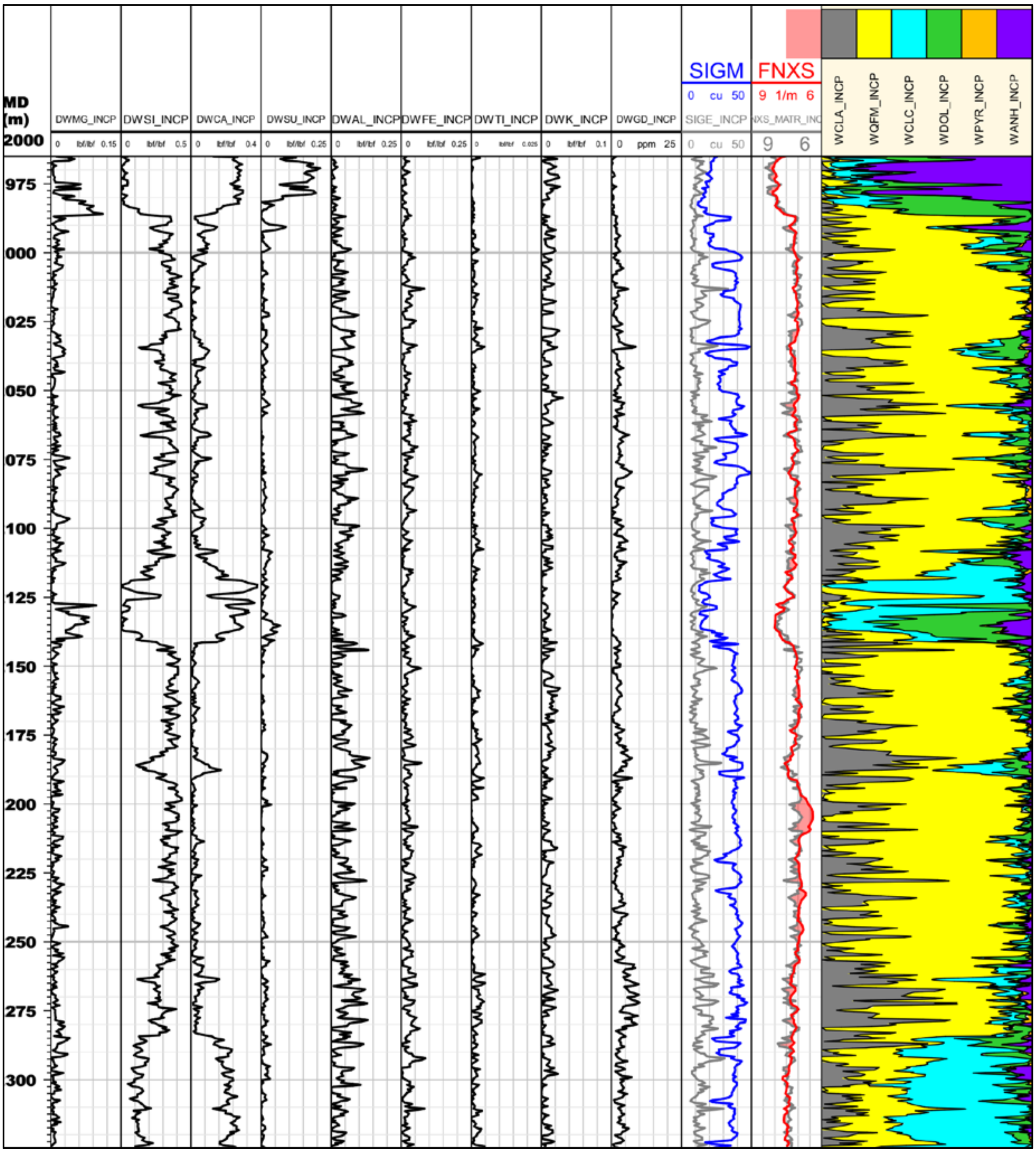

Figure 7. Spectroscopy results for the clastic section, including dry weight if main formation elements and final Spectrolith results of the generate mineral weights (last track).

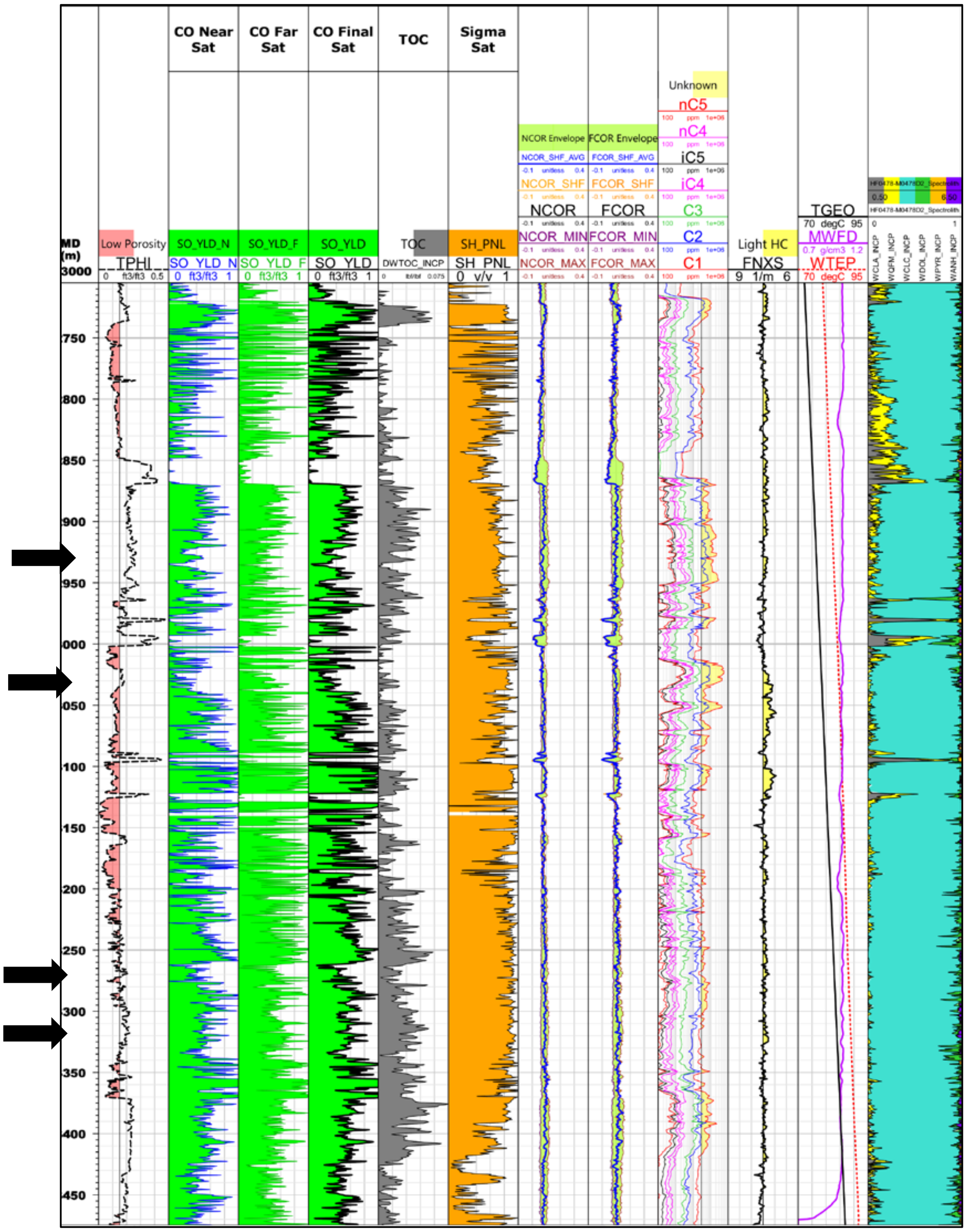

Figure 8. Comprehensive petrophysical evaluation results of the carbonate section. Low porosity zones are highlighted with red colour 2nd track. Finalized C/O saturation (SO_YLD, averaged from Near & Far detector readings) is highlighted with green shading in 5th track while Sigma-saturation (SH-PNL) is highlighted in orange colour in 7th track. TOC fraction is highlighted in grey colour in 6th track and FNXS in 11th track. Spectrolith is presented in track 13. The black arrows indicate potential zones with higher oil mobility.

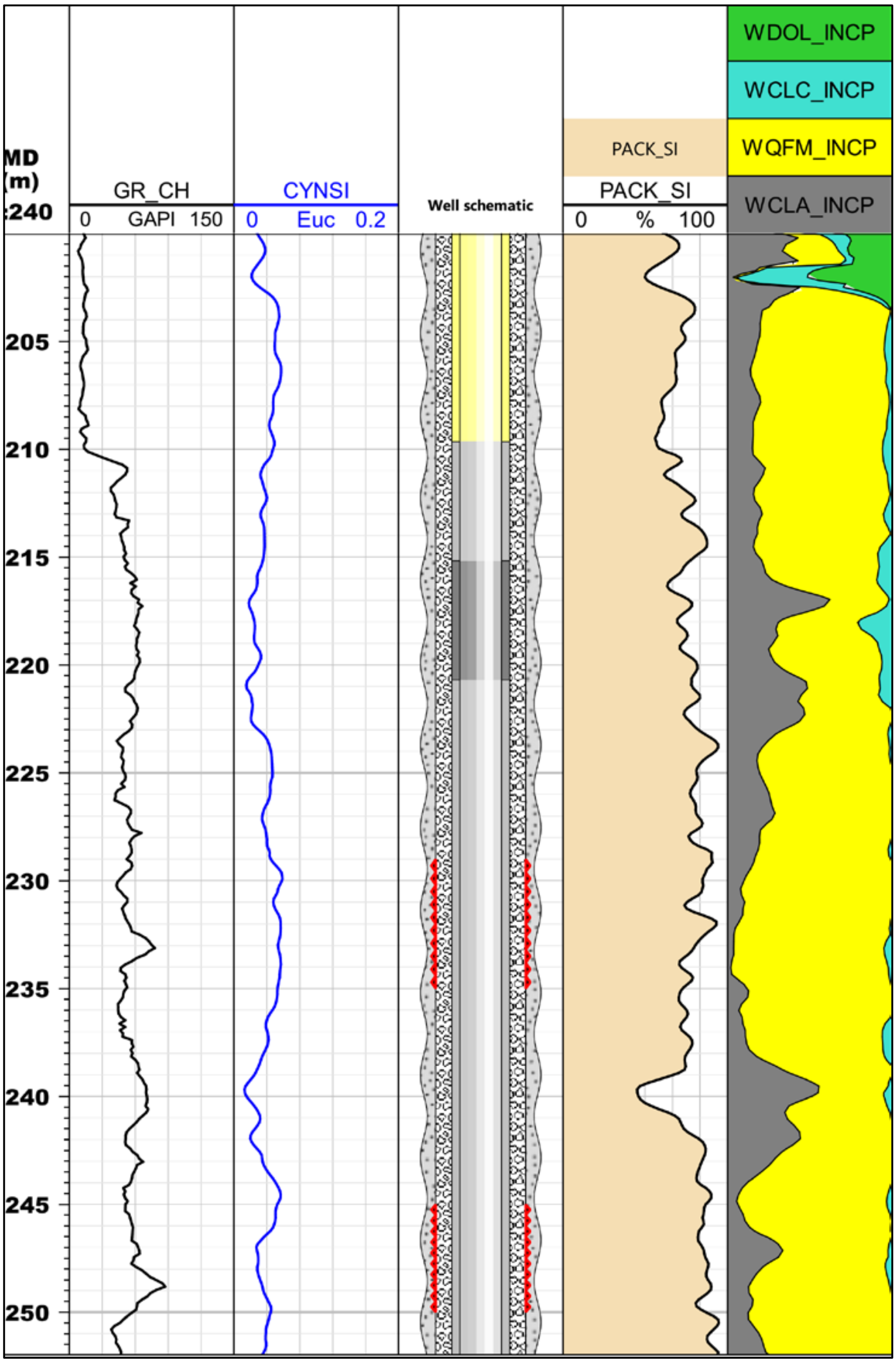

Figure 9. Gravel pack evaluation with pulsed neutron Silicon yield. The gravel pack quality indicator curve Pack Silicon Index (PACK_SI) is shown in the 5th track.