Evolution and Evaluation of a Shallow-Marine LRLC Reservoir with Advanced Well-Log Measurements: A Case Study from Offshore Nigeria*

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Abstract

Low-resistivity, low-contrast (LRLC) reservoirs are often difficult to evaluate because important pay zones could be overlooked or completely bypassed if an accurate and comprehensive evaluation program is not considered. It is imperative to understand the geological evolution of such reservoirs in order to understand their distribution and associated petrophysical properties and their variation in the field.

The Tertiary shallow-marine-clastic LRLC reservoirs in the study area are interpreted to have been deposited in a deltaic environment offshore Nigeria, in predominantly distal environment. Borehole image interpretation suggests that the low-resistivity contrast is attributed to dispersed shale, probably due to the coating of clay around the sand grains in the toe part of a delta front in major coarsening-up and minor fining-up sequences; sedimentation being controlled by a developing delta. Petrophysical data recorded at high resolution correlates, indicating the main causes of LRLC pay zone are commonly the clay content and distribution and small grain sizes within the reservoir rock, resulting in low-resistivity values and more irreducible water associated with the increased surface area.

Advanced nuclear magnetic resonance (NMR) measurements are integrated with spectroscopy and sonic data to evaluate shaliness, porosity, and permeability level-by-level, better defining any possible minerals contribution and nullifying the clay effect. High-resolution NMR detailed rock description and magnetic resonance (T1 and T2) signal distributions portray heterogeneous grain-size distribution with increased amount of finer grains and small clay particles coating the sand grains or filling the pore throats between framework grains, hence altering the reservoir properties. NMR diffusion-based logging, and resulting fluid maps, confirms the presence of oil. The analysis of porosity, water volumes, and saturation components, computed from the petrophysical data, reveal such reservoir, despite its complexity and overall lowered rock quality, could be produced free of water breakthrough.

This case study highlights the interesting relation between the depositional facies in LRLC environment and its relation to the development and evaluation of the petrophysical environment. The workflow adopted in this study helps to characterize and exploit similar reservoirs offshore Nigeria with better evaluation results and producibility prediction.

Introduction

LRLC pay implies a lack of resistivity contrast between pay sands and adjacent shales or wet zones. Such reservoirs have been attracting attention for a long time; and the advances in technology, both for evaluation and exploitation have made such reservoirs even more important in the changing economic equations. It is imperative to understand the evolution of such reservoirs before the evaluation is attempted. LRLC reservoirs are found in all major siliciclastic depositional environments, except alluvial fans and aeolian deposits (Darling and Sneider, 1993).

Clay minerals with their water-filled microporosity and ability to exchange cations with pore fluids are the most common causes of LRLC reservoirs. The clays, in order of their highest to lowest exchange capacity; and therefore their effect on the suppression of electrical logs are: smectite, mixed layered smectite/illite, illite, mixed layered illite/chlorite, chlorite, and kaolinite.

The clays are deposited and/or formed during diagenesis (Darling and Sneider, 1993). Shale, primarily composed of clay minerals, therefore, can show different porosity (Figure 1) depending upon its distribution in the reservoirs (Serra, 1990).

Pay zones that produce low resistivity or low-contrast log responses are influenced by a variety of factors associated with mineralogy, water salinity, and microporosity, as well as bed thickness, dip, and anisotropy. The classical thin-bedded, low-resistivity pays can actually be resolved by triaxial induction resistivity and borehole image logs; and at that high resolution they are not low-contrast pays (Claverie et al., 2010). However, dispersed clays can actually be difficult to resolve and add even more to complexity. Sneider and Kuhla (1993) postulated 4 different types of settings for LRLC environment (Figure 2).

Study Area: Location and Background Geology

The study area is located offshore Nigeria in a water depth of about 10m in the northeastern sector of OML 123 acreage in the Niger Delta province. The OML 123 acreage is owned by Addax Petroleum Development Nigeria Limited (APDNL). The field lies approximately 1.5 km from the eastern limit of the OML123 concession, which extends along the Nigeria-Cameroon border (Figure 3).

Oil was discovered in 1972 in this acreage and the oilfield comprises five independent fault blocks. A number of wells have penetrated the P and I sands of the Miocene Biafra Member (Figure 4), where the oil is distributed in five reservoirs, P-6, P-7, I-2, I-3, and I-4. The Biafra Member which includes all reservoirs from P-4 to I-4 (Figure 4) is a deltaic sequence made-up of numerous stacked, upward-coarsening units, with prodelta shales and silts near the base, grading upwards into medium- to coarse-grained upper-delta and shallow-marine sandstones at the top. The reservoir sandstones of the Biafra Member were deposited in a high-energy, wave-dominated deltaic environment, prograding over the thick prodelta shales of the Akata Formation. The Akata Formation is the main hydrocarbon source rock for the overlying Biafra reservoir sands. The study well was drilled into a fault block—with core provided along with LRLC logging data to further improve and define the other I-3 series sands and other known LRLC reservoirs.

Regional Setting and Stratigraphy

The Niger Delta structure and stratigraphy are the result of interplay between sediment supply and subsidence associated with syn- and post-sedimentary listric normal faulting. These faults are part of a major network of growth faults trending across the delta from northwest to southeast, dividing it into a number of structural fault blocks or macrostructures, each forming a sedimentary depocentre. These depocentres become progressively younger southwards; Eocene in the north to Pliocene-Quaternary age in the south. The structural configuration of the study area is controlled by a large growth fault and a series of east-west-trending and south-dipping synthetic faults that effectively compartmentalise the field into a series of down-stepping fault blocks. The reservoir geometry and architecture is controlled by this large growth fault, which is also responsible for the presence of numerous transgressive shales and silty units interbedded within the P and I Sands. These shaly-silty units are laterally extensive and coincide with flooding events associated with major subsidence movements along the growth fault.

Formation Evaluation Challenges in LRLC Reservoir

Although LRLC reservoirs have been under production for many years, their identification and the calculation of their reserves and flow properties remains a difficult challenge (Claverie et al., 2010). Often low apparent resistivity and high-bound fluid volumes are caused by shale laminae or layers of conductive clay and fine grains within the reservoir rock. Concomitance of fresh formation salinities also contributes to low-contrast conditions, hence posing difficulties to any conventional evaluation methodology.

Multiple approaches exist to describe distribution, rock properties, and flow potential within thin-bedded LRLC reservoirs. Bimodal anisotropic methods are routinely applied for timely and accurate evaluation of similar cases of reservoir layers. The fractional volume of coarse- and fine-grained rock is determined and the true resistivity of coarse-grained fractions computed to derive correct pore volumes and saturation within a certain rock thickness.

However, due to rock heterogeneity and complex mineral structure, influence of the varying clay volume and types, presence of dispersed shale in the sand layer sand its inherent effect on log responses, a more complex evaluation model is required to account for these (Figure 5).

Interaction between clay particles and water results in lower resistivity values usually associated to high non-producible bound-water values, whose amount varies with clay type and pore-throat radius. Mineral content in the micropore is, in fact, one of the main factors explaining high, but immovable, water content. Microporosity (contributing to the non-effective component) is expected and needs to be quantified as it may constitute a substantial percentage of total porosity and lead to higher estimation of water saturation.

Finally, rock texture and structural position (relative to the free-water level) are additional factors with strong influence on irreducible fluid amounts and residual hydrocarbon saturations; hence playing an important role in determining whether a low-resistivity pay zone will produce water or hydrocarbon.

Understanding of those interrelated factors become particularly critical for LRLC pay analysis when complex settings make it difficult to identify the main source of LRLC from log response only (i.e., absence of anisotropy and thin beds cannot be identified as source of LRLC). As the present case study illustrates, existing interpretation models are re-examined and upgraded to account for any, or a combination, of the added complexities and offer the greatest sensitivity to the "healthy components" within the rock framework accounting for all shale and fine-grain content.

A comprehensive well-log program, possibly supported by core-data integration, is essential. Geological evolution and deposition of the subsurface environment have to be considered as a foundation of robust formation evaluation.

Well-Log Analysis and Depositional Environment

High-resolution borehole images in one study-well were used to understand the geological environment in the subsurface. The borehole images show an absence of thin-bedded alternation, thereby suggesting lack of laminations as the reason for the reduced resistivity. If laminations below 10mm thickness are present, they cannot be resolved. However; with the interpretation of depositional environment both with seismic and well logs, the study interval appears to be part of deltaic sedimentation; more so in distal parts. Reconstruction of the well trajectory and subsurface geology, interpreted with borehole images, suggests that the well intersected a rollover anticline; and the structural elements also suggest possible fractures that are parallel to the regional main growth fault trend. In the background of the deltaic environment, the study interval was interpreted to be part of the toe-end of the delta front (Figure 6).

The borehole images were further interpreted for textural variations, and the study interval was studied for the facies association. The environment of deposition was inferred to be of medium- to low energy, thereby suggesting this to be interpreted as the toe-end of the delta front.

Borehole images (Figure 7) show a column of fine sands, around 50m thick with a subtle deflection of GR to left. The environment of deposition is interpreted as the toe-end of a delta front, in the vicinity of prodelta (Figure 8). No visible traces of thin beds were observed on the borehole image (resolution 10mm).

Petrophysical Well-Log Analysis

Multiarray triaxial induction measurement is the resistivity tool selected to derive accurate sand resistivity and identify any possible lamination effect within the LRLC interval. Elemental yields from the nuclear spectroscopy tool are measured to quantify mineral volumes and improve clay-volume estimation in presence of radioactive minerals within the sand fraction. High Resolution multi-frequency magnetic resonance logs, together with epithermal neutron porosity and formation density tools, define rock quality level-by-level. Rock physics and elastic properties of the media measured depth-by-depth with the help of dipole sonic tool are also considered to better understand the shale content and variations within and around the reservoir of interest. High-definition borehole images and their findings as described in the previous section support the rock analysis and reserve estimation.

An integrated step-by-step interpretation workflow (Figure 9) is applied to best describe the LRLC reservoir interval, distinguish and characterize those shale components that are able to alter reservoir properties, and define the sand-layer contribution to hydrocarbon production, honoring the geological framework.

Knowledge of mineralogy, rock volumes, and porosity estimation are critical prerequisites to any complex reservoir evaluation. Triaxial induction measurements are inverted for true sand resistivity analysis performed in synergy with enhanced porosity and mineralogy investigation. The data are integrated with multi-frequency high-resolution magnetic resonance for rock quality and fluid ability to move into a modern Reservoir Sand Analysis (RSA), where a refined dual water model can be used for saturation.

Accounting for shale anisotropy and clay types within the sandstone is made. In the sand portion itself, a fraction of dispersed clay (shale) is evaluated, starting from knowledge of total “geochemical” shale fraction from spectroscopy technology and laminar shale from the anisotropic shale interval.

The data are further investigated to better characterize clay distribution and average grain sizes leading to a more refined fluid-flow prediction. Another main innovation is the combination of dipole sonic, processed for compressional and shear anisotropy around the borehole, to find proper interrelations between petrophysical and elastic rock properties to help in validating the considerable effect of dispersed clay.

Multi-frequency magnetic resonance saturation profiling provides alternative hydrocarbon volume estimation; the measurements are particularly useful to confirm pay thickness and possible fluid contacts in the absence of resistivity contrast.

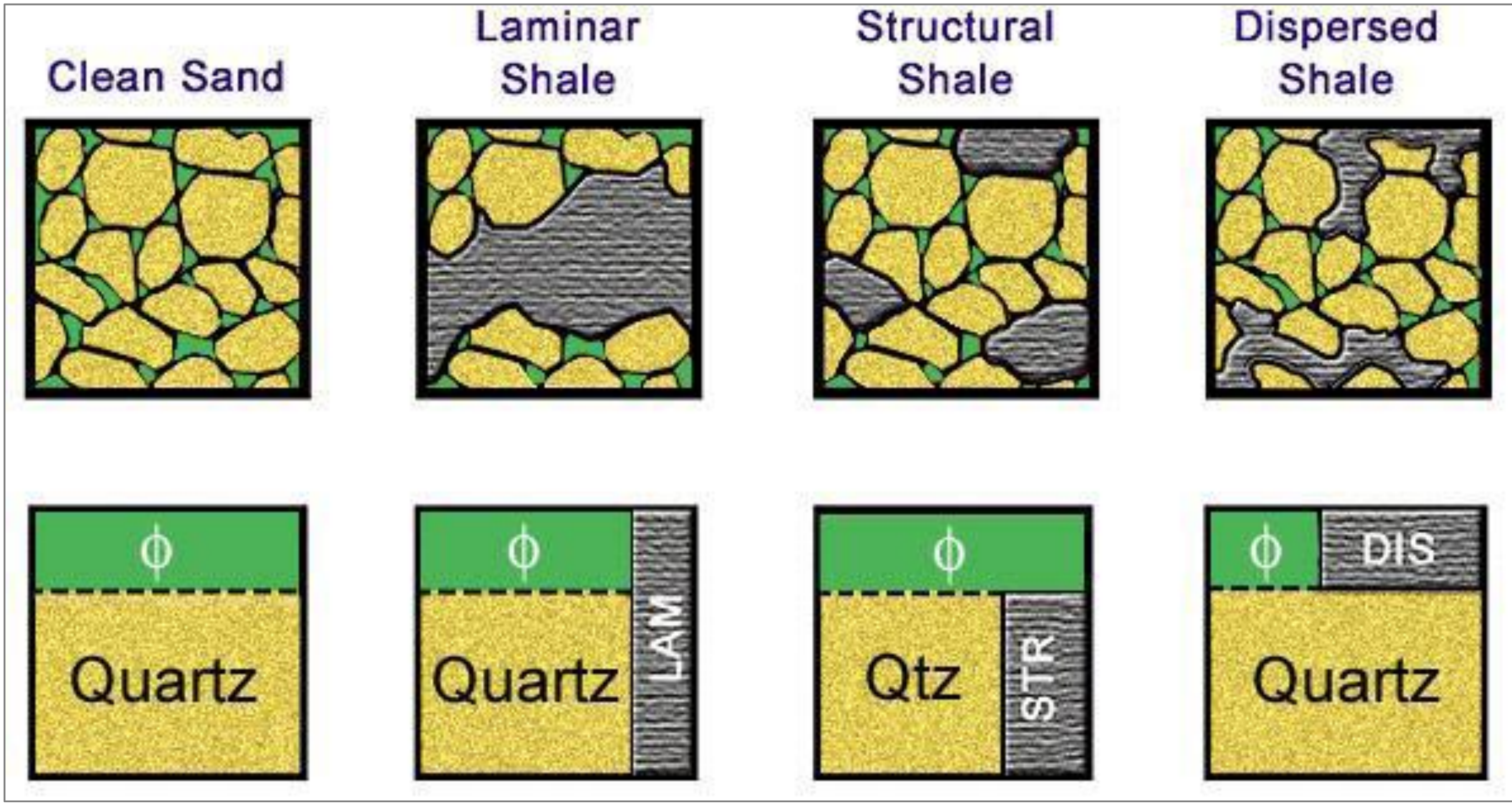

Figure 1. Distribution of clay in reservoirs (from Serra, 1990)

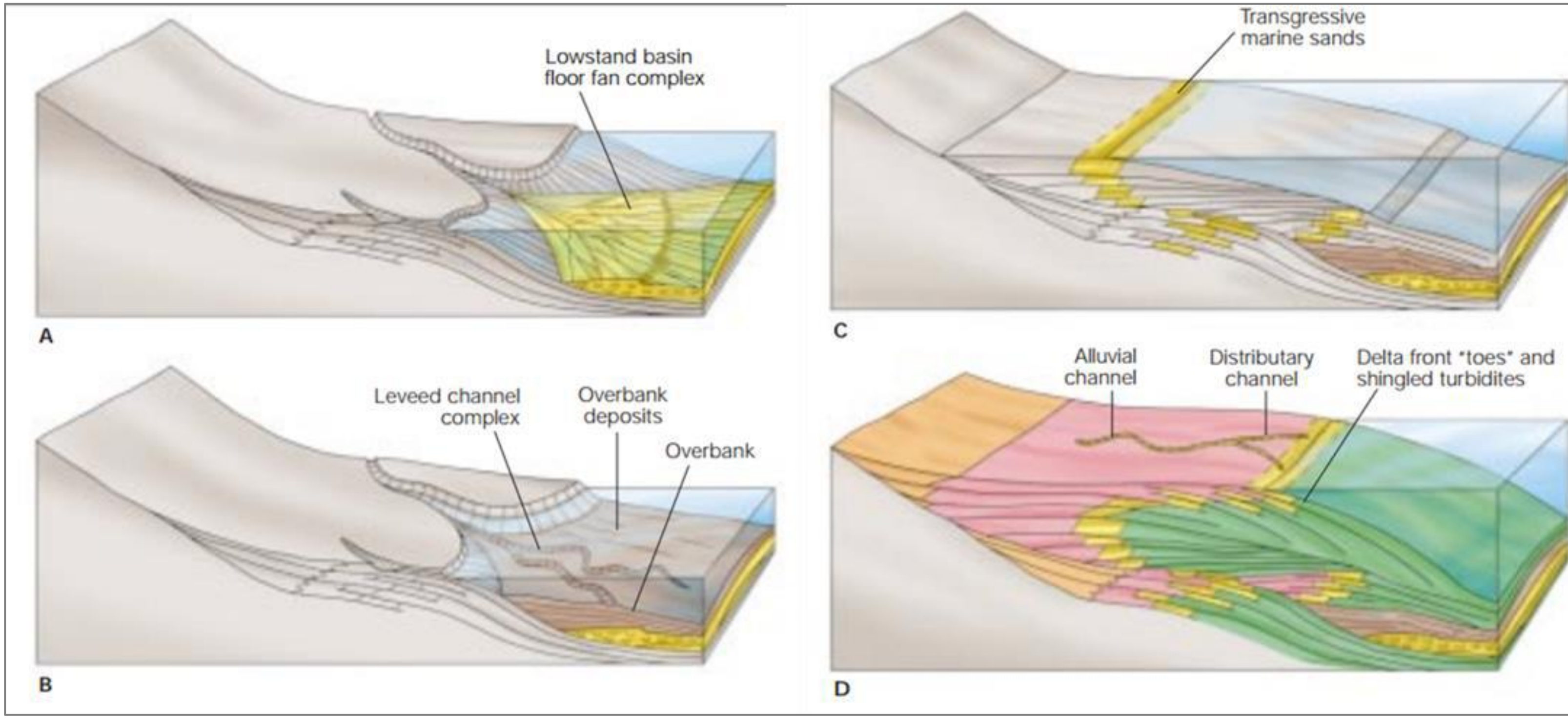

Figure 2. LRLC environments(after Sneider and Kuhla, 1993). A. Lowstand basin floor fan complex. B. Deepwater levee-channel complexes. C. Transgressive marine sands. D. i)Lower parts of delta-front deposits; ii) laminated silt-shale-sand intervals in fluvial reaches.

Figure 3. Study area (red rectangle).

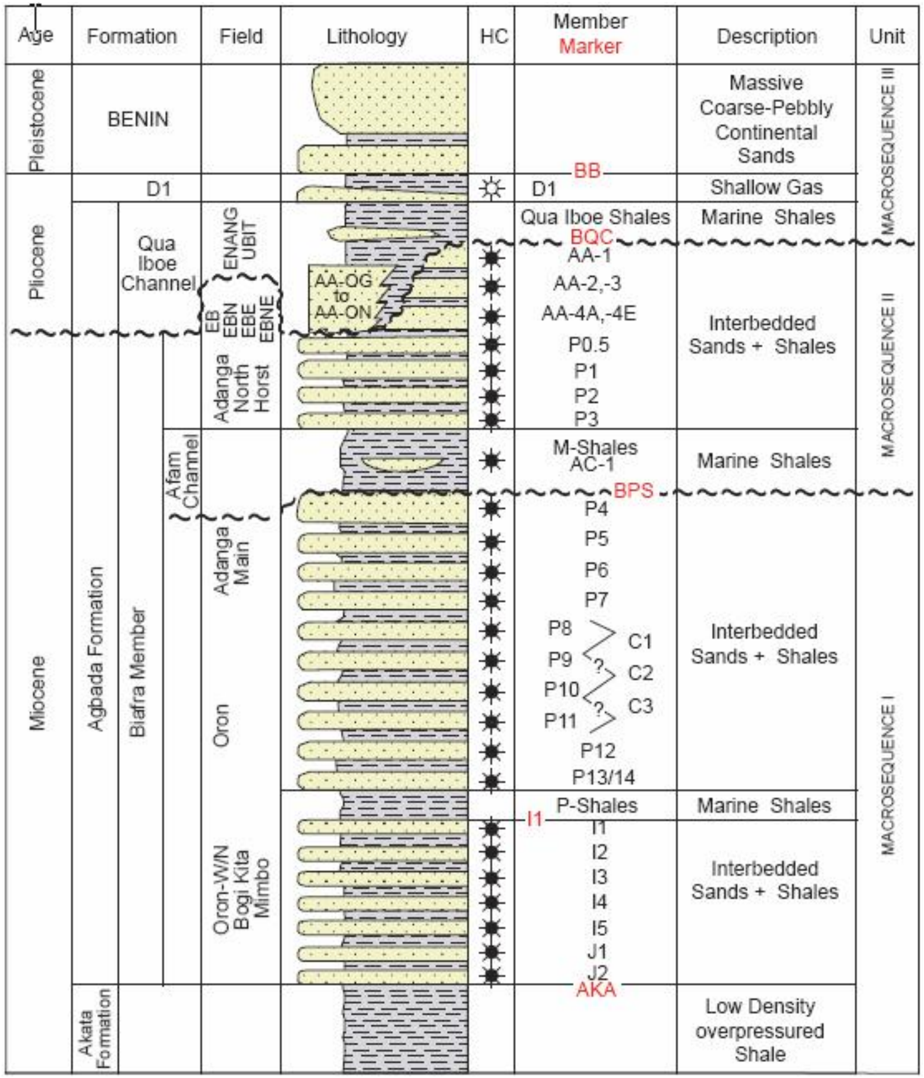

Figure 4. Generalized stratigraphy in the study area.

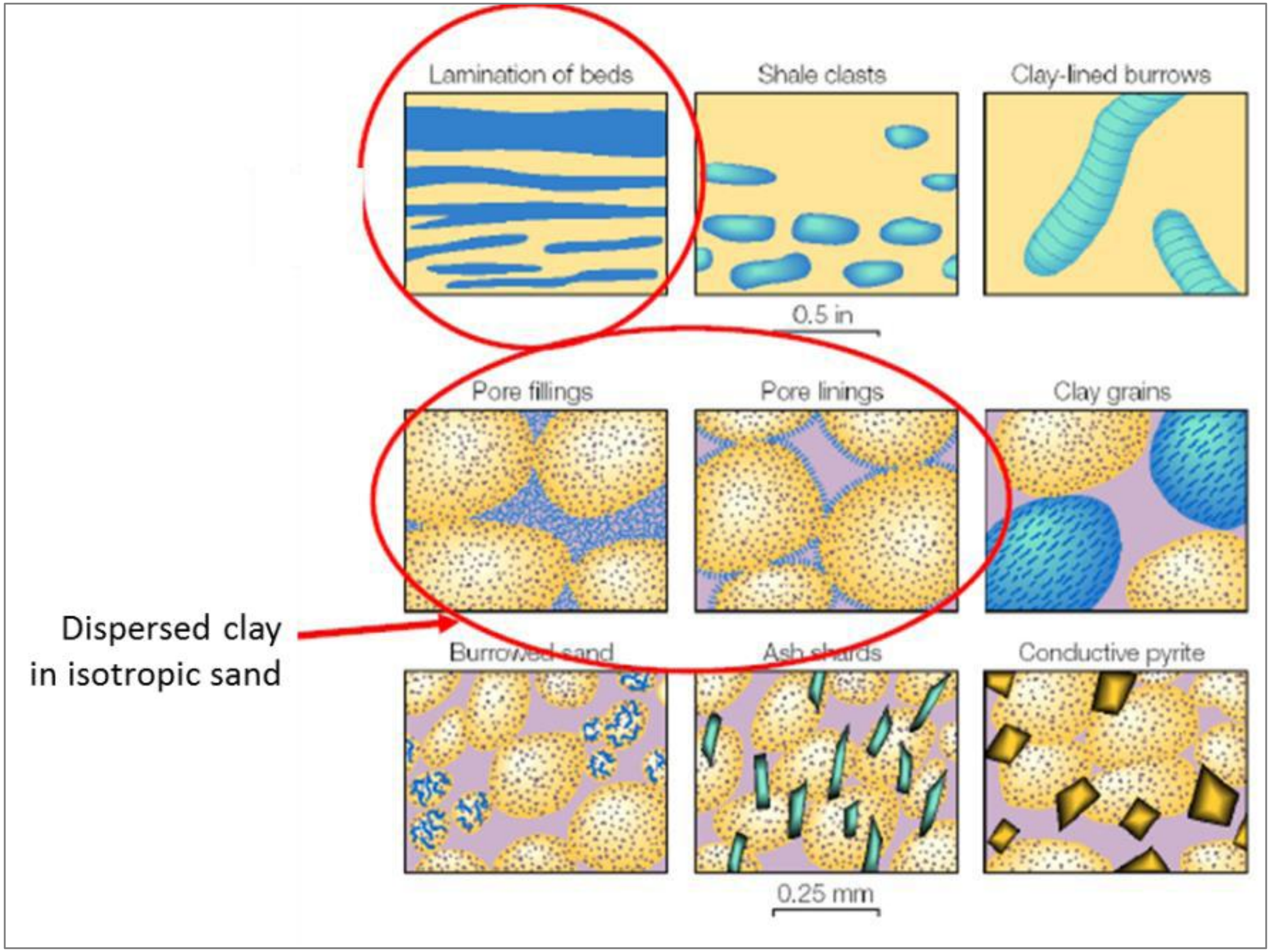

Figure 5. Evidence of dispersed clay in isotropic sand; highlighted are anisotropic shale, a characteristic property of most shales in the region (after Sneider and Kuhla, 1993).

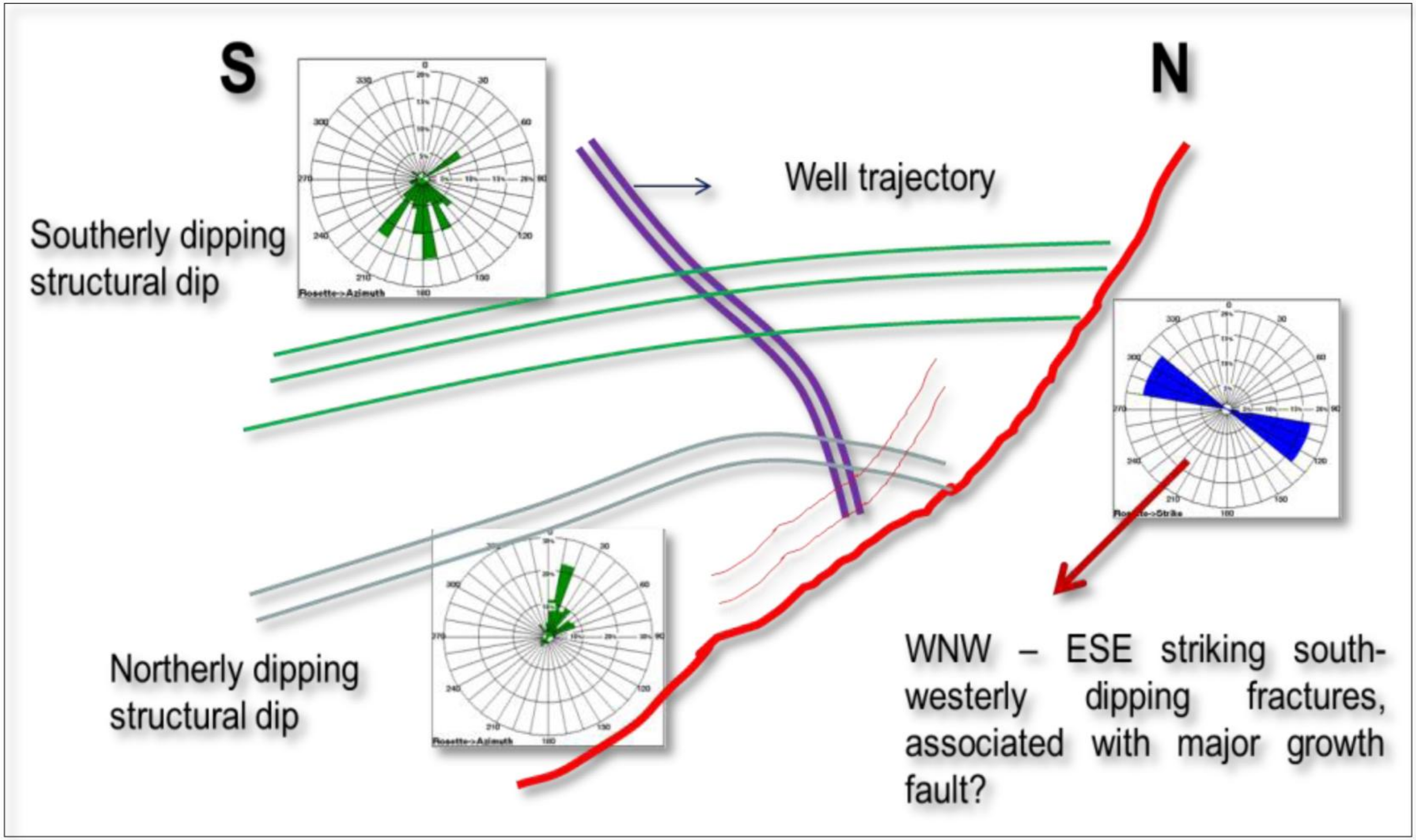

Figure 6. Schematic cross-section of the subsurface.

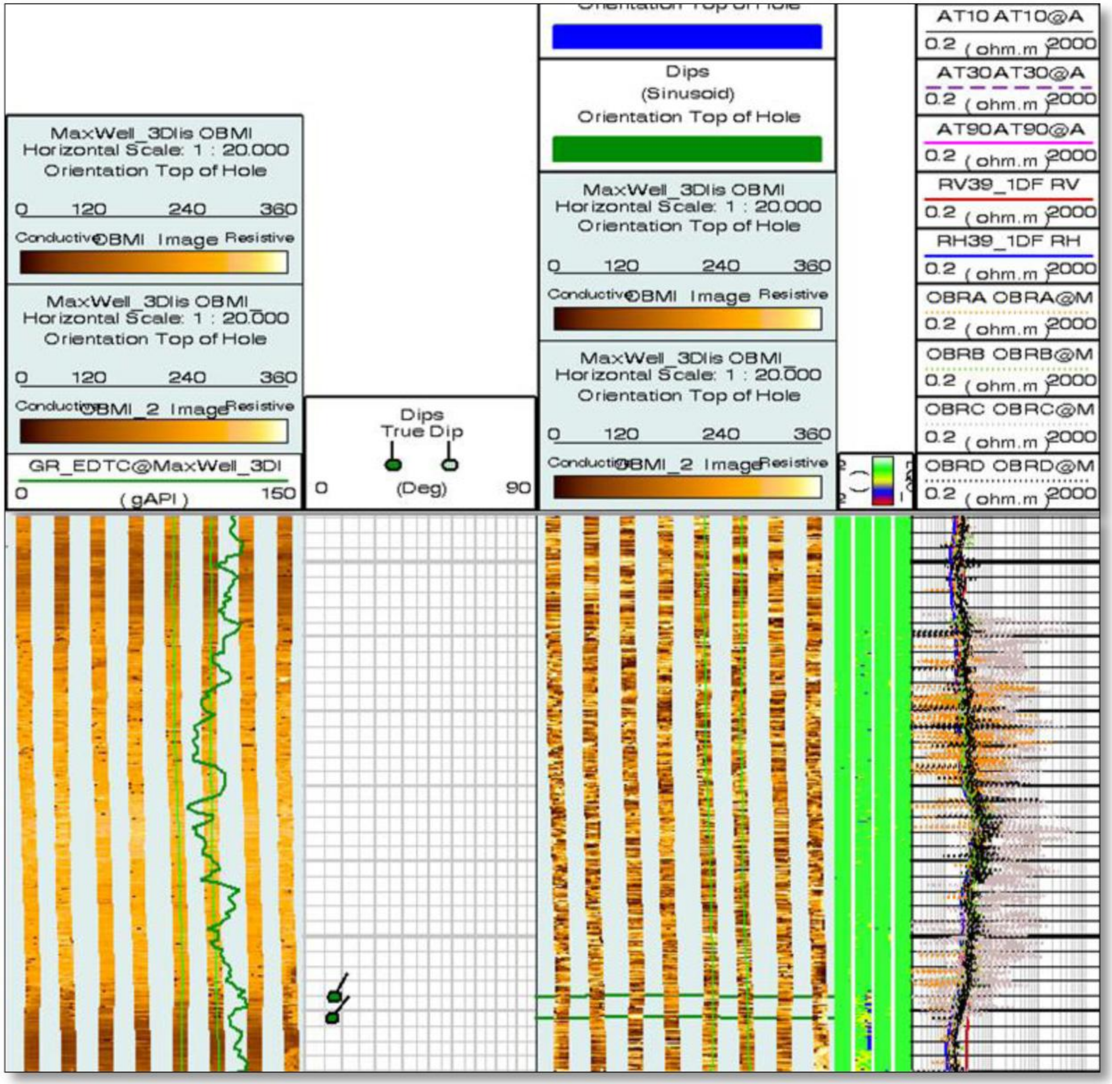

Figure 7. Borehole images, showing~50m LRLC (the brighter shades of color on static image, 1st track).

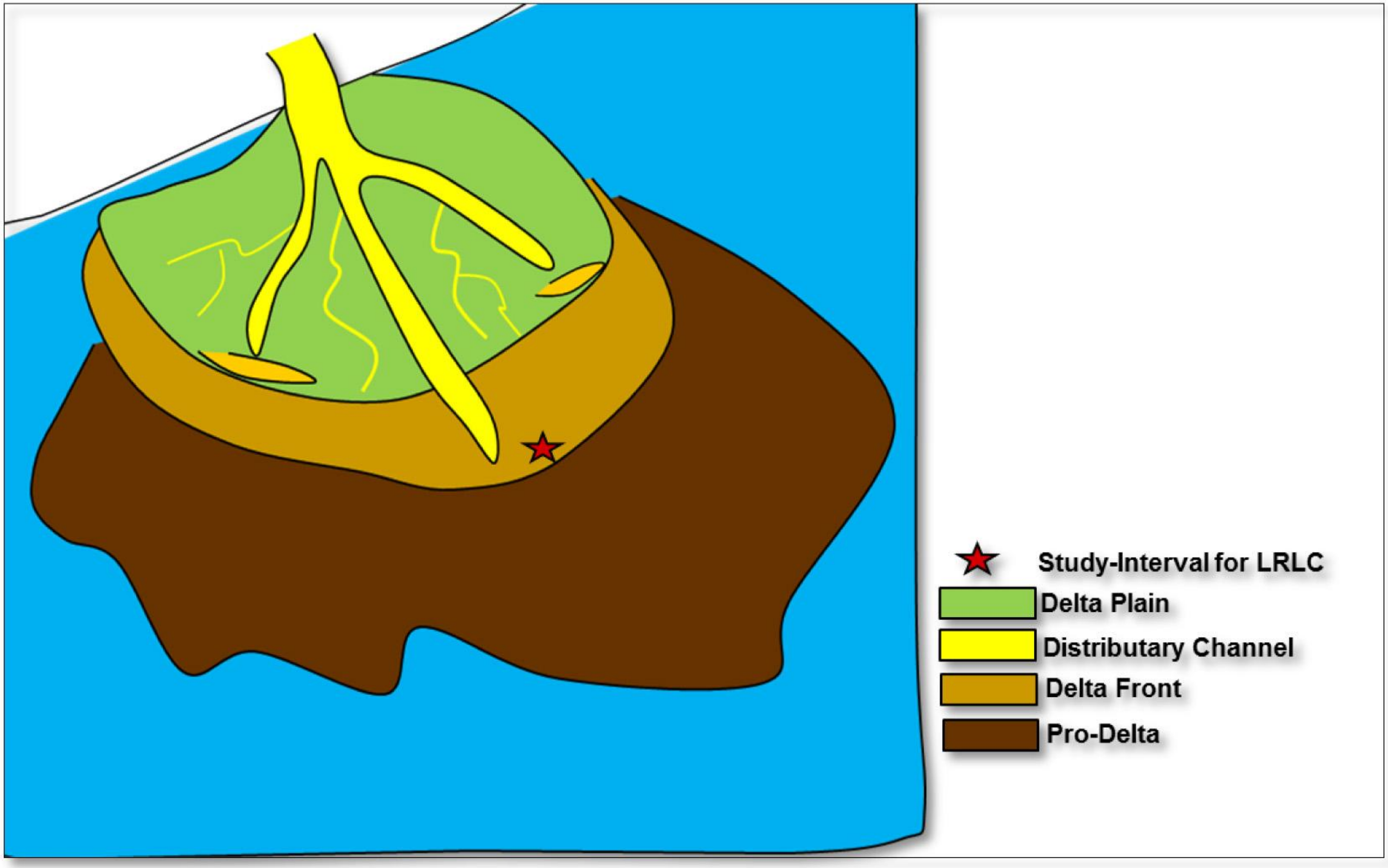

Figure 8. Inferred depositional environment for LRLC in the study area.

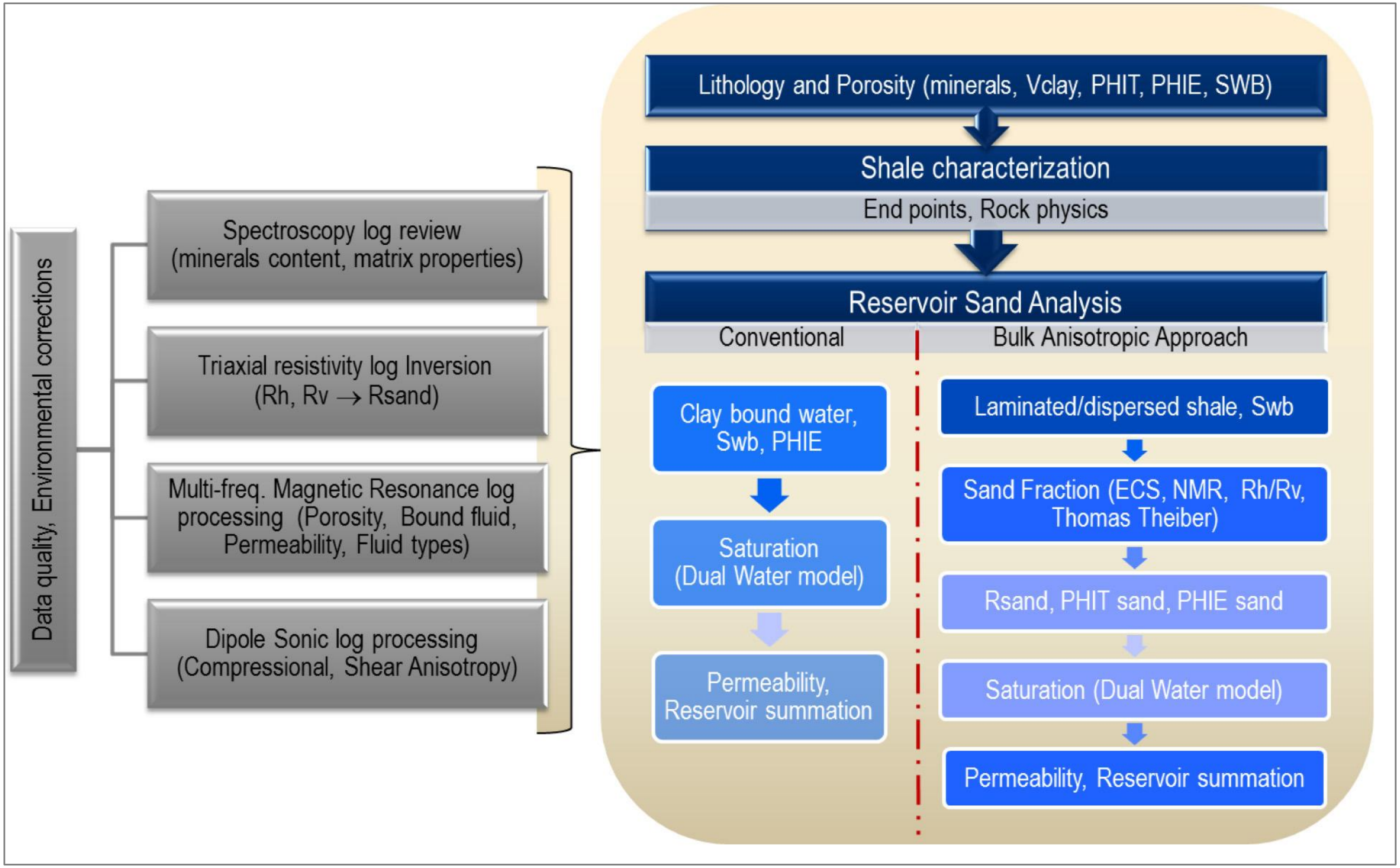

Figure 9. Main petrophysical evaluation workflow adopted for the study

Petrophysical Data Summary and Results

As illustrated in the composite log plot in Figure 10, one main peculiarity of this reservoir is the absence of resistivity anisotropy as indicated by relatively low values of electrical resistivity, both measured horizontally and vertically to the beds. As detailed below, the log analysis partly attributes this to unusual distribution of dispersed shale, gradually interbedded with silty sand, as well as the presence of increased finer grains and clay particles (mix of different clay types) coating the sand grains and filling the pore throats between coarser components.

The Rv/Rh resistivity ratio indicates laminated shale content, and in fact, local experience tells us that shales in the region are intrinsically anisotropic in nature. Based on those observations a "clean shale" point with laminations due to clay platelets and structure is selected. NMR signal distributions and bound fluid content at the specific depths validate the assumption that this is the shale point (Figure 11).

The definition of clay point properties (Rv Rh plot) is an essential component of the RSA resistivity processing step. Rv, Rh resistivity values on laminated shale fraction are defined level-by-level using a novel approach (anchor point method) to honour its structural and compositional complexity, intrinsic variation in clay minerals content, water resistivity, and variable degree of compaction with depth (Cavalleri and Allen, 2013).

However, distributions of porosity and clay volume within the LRLC reservoir show specific sand-shale allocations, with signatures which are typical of dispersed-clay sandstone and dispersed quartz shale, validating the need to also account for dispersed-clay contribution in the system; structural components have limited effect on rock petrophysical properties.

The dispersed clay within the sandstone matrix is computed to be the difference between total shale fraction and laminated shale. Based on this representation of the complex system, the end points for laminated shale, structural, dispersed (and structural) and clean sand are defined as described in the plot in Figure 12. Laminated shale is represented by the trend line (in red) between sand and shale end points, where the sands are assumed to be clean. The points plotting below the trend line are laminated shale and sand with dispersed clay; hence, a dispersed shaly sand model applies.

The inclusion of sonic logs to the petrophysical model provides an alternative method to characterize dispersed clay content and effect (Marion et al., 1992). As documented in various technical articles, acoustic wave propagation is not only linked to the type of minerals and the fluid within, but also to the structure of the matrix and the presence of clays within the sand grains altering the rock's elastic capacity. Furthermore, not only the presence but the distribution of the shales (dispersed, laminated or structural) will have different impacts on the propagation of acoustic waveforms. In the same way, changes in porosity will impact the acoustic velocities.

Experiments on synthetic rocks (Marion et al., 1992) indicate that, if clay occupies part of the pore space and is not located between the grain contacts, the elastic velocities will increase with increasing clay content. This trend agrees with the expected impact of dispersed clay distribution of reservoir properties of the sand, such as porosity and permeability; hence the opportunity to correctly link the various log measurements to better understand the rock components.

The cross-plots in Figure 13 exhibit the relationships between total porosity (matrix corrected), total clay volume, P- and S-velocities across the LRLC reservoir interval. The plots exhibit the V-shaped structure characteristic of a system with 2 main components:

a) grain-supported system where quartz-to-quartz grain contact supports the rock and the pore space is filled with fluid (or dispersed clay),

b) matrix-supported where laminations are the main structure.

The indication of typical dispersed clay trends within the grain-supported arm of the V shape (Liu et al., 2014) help in validating the log-based physics model adopted and the components and rules defined for the complete RSA interpretation on LRLC.

In particular, the right-side crossplot relates total porosity (matrix corrected) to total volume of clay; the trend indicates that in high total porosity the pore space initially occupied by fluids is replaced by dispersed clay; hence the total porosity decreases rapidly as the volume of clay increases until we assume that only a clay contribution fills the pores. The second arrow pointing slightly upward refers to the areas where the rock is shale or shale laminae (shale layers surrounding the reservoir); all total porosity values here comes from shale with water content strictly related to the clay mineral mixture. It is clear that the fraction of shale will have different impact on the total porosity depending on the distribution of the clay. For the same fraction of shale, dispersed shale will reduce the total porosity of the system faster than laminated shale.

The middle crossplot provides another view by linking P- and S- velocities to total porosity. As expected, with increase in porosity there is a reduction of velocities; however, in the grain-supported system, P velocity decreases as the total porosity increases at a different rate when compared to the matrix-supported system, where laminations reduce velocities at a faster rate. S velocity is not affected by the fluid properties; hence, it shows a different trend on the grain-supported system; however, a very similar trend is seen on the lamination when compared to P velocities.

The elastic P and S velocities versus total-clay volumes are described in the right crossplot; the trends correlate with the total porosity vs clay volume relationship; within the sands (grain-domain) P-velocities increase as the dispersed clay content increases, until a certain limit where the rock is shale and P-velocity values start decreasing as clay content increases, due to clay platelets and structure. Complications related to the presence of hydrocarbon within the LRLC zone of interest need to be considered when interpreting those relationships.

The investigation of the rock properties and innovative methods are the main ingredient of the reservoir sand analysis to derive quality and accurate fluid saturation and predict reservoir producibility. Figure 14 shows the main interpretation of results of the RSA analysis across the LRLC reservoir. The rocks are heterogeneous in grain size, and reservoir properties vary with changing porosity and density values. There is a general coarsening-upward from the basal shale to the LRLC potential reservoir, and fining-up from the reservoir to the capping shale. Mineral assemblage and gamma-ray values within the reservoir confirm the presence of radioactive minerals within the sandstone layers not associated with the clays.

High-resolution magnetic resonance measurements compute high irreducible water saturation values, which may suggest the presence of smectite as one of predominant clay types; moreover, literature indicates the smectite clay content in the reservoir zone could actually be richer than in the shale areas above and below. This log interpretation is in line with regional information proving that Niger Delta clays are mostly a mixture of kaolinite and smectite, with little to variable illite concentrations.

Despite the apparent high-water saturation and increased irreducible water content, and with the low permeability of the reservoir and dense radioactive minerals content complicating the investigation, an accurate description of rock and fluids is performed. The non-producible bound water, evaluated by high-resolution magnetic resonance well logs in terms of non-movable fractions within small pore sizes, is directly compared to the bulk volume of water computed by the RSA in order to confirm that the reservoir would produce only hydrocarbons. This evidence is then confirmed by downhole pressure testing and fluid analysis and further well testing.

High-resolution resistivity data from borehole images on a stratigraphic scale correlates with the petrophysical information, also indicating “dirty” or silty sands with subtle coarsening-up sequence overlain by a subtle fining-up sequence in an intertidal setting.

In addition, the review of magnetic resonance fluid maps recorded at different depths of investigation support the dispersed shaly-sand-model results, interpreting the distribution of fluids radially, at multiple independent depths of investigation, to confirm movable fluid fractions, despite poor rock quality. This is critical data to guide the operator's decision-making process at this early stage of the well development.

Summary

LRLC reservoirs have been known to exist in West Africa for quite some time. With the advent of advanced well-log measurements, better characterization can be achieved where evaluation honors the evolution history of such reservoirs. In the study area, shallow-marine Tertiary clastic reservoirs in the Niger delta were studied for the LRLC reservoirs, where clay minerals and their distribution appear to be the major reason for a reduction in resistivity in the reservoir section. The inferred depositional environment for the LRLC sands is the toe-end of a delta front.

Smectite content is known to increase in such reservoirs in the region; some mineralogical analysis on full-bore core would be carried out to quantify exact clays content in the target reservoir. Borehole images confirmed the absence of thin beds in the study interval (or the thin beds, if present, would be less than 10mm thickness, because that is the resolution of the borehole images in the study). The detailed analysis with sonic measurements shows clear trends of two different clay distributions within the sands and the shales above and below. The Reservoir Sand Analysis, with advanced measurements of NMR and spectroscopy, suggests high content of irreducible water; thereby implying water-free production from these intervals.

The results of this study show the value of integrated approaches and improvements in reservoir description from multiple high-resolution logging measurements (at an early stage of reservoir development) into reservoir models.

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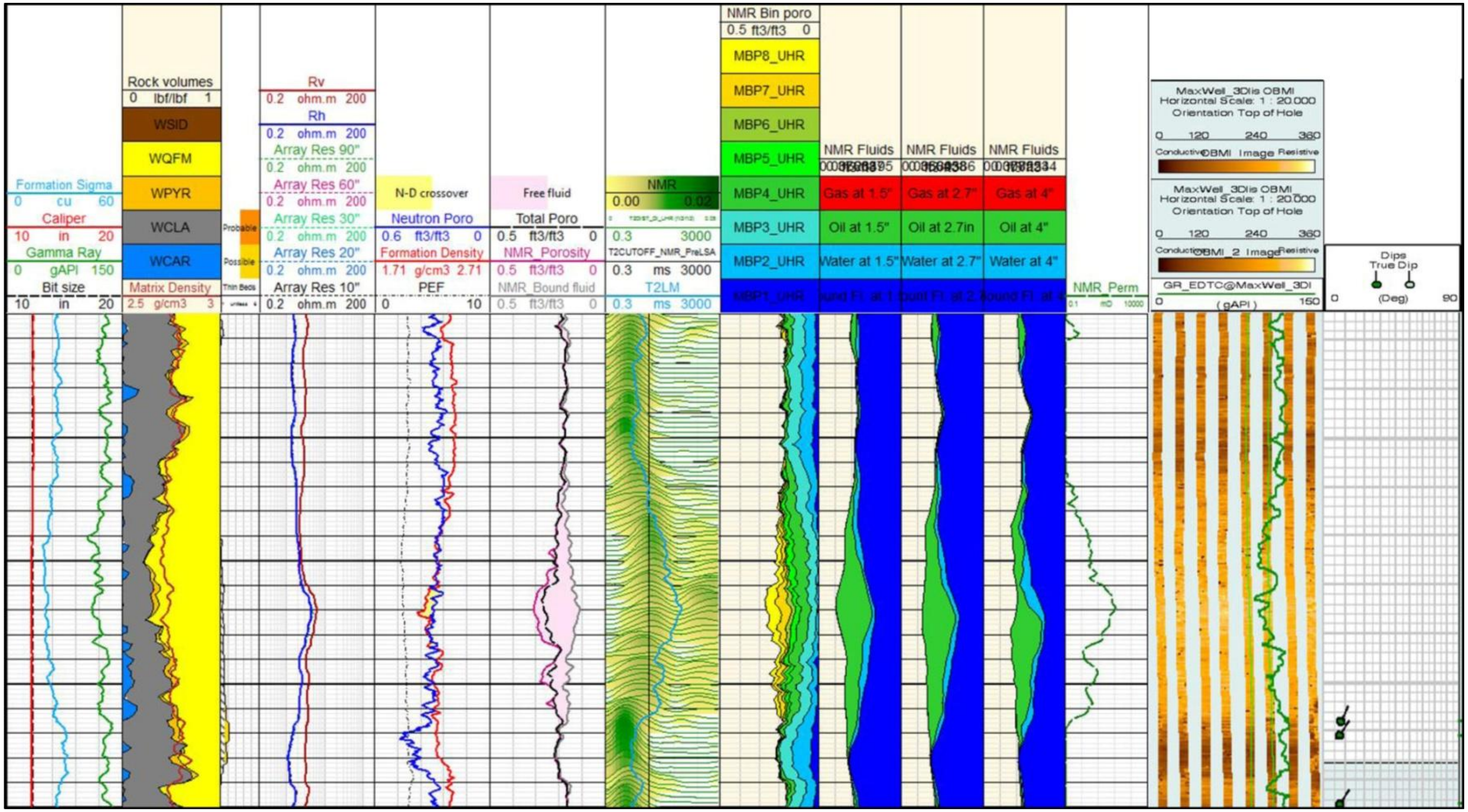

Figure 10. Summary of main petrophysical logs recorded across the LRLC reservoir of interest – Plot scale is1:200ft MD. The study interval in the plot is 100 ft.

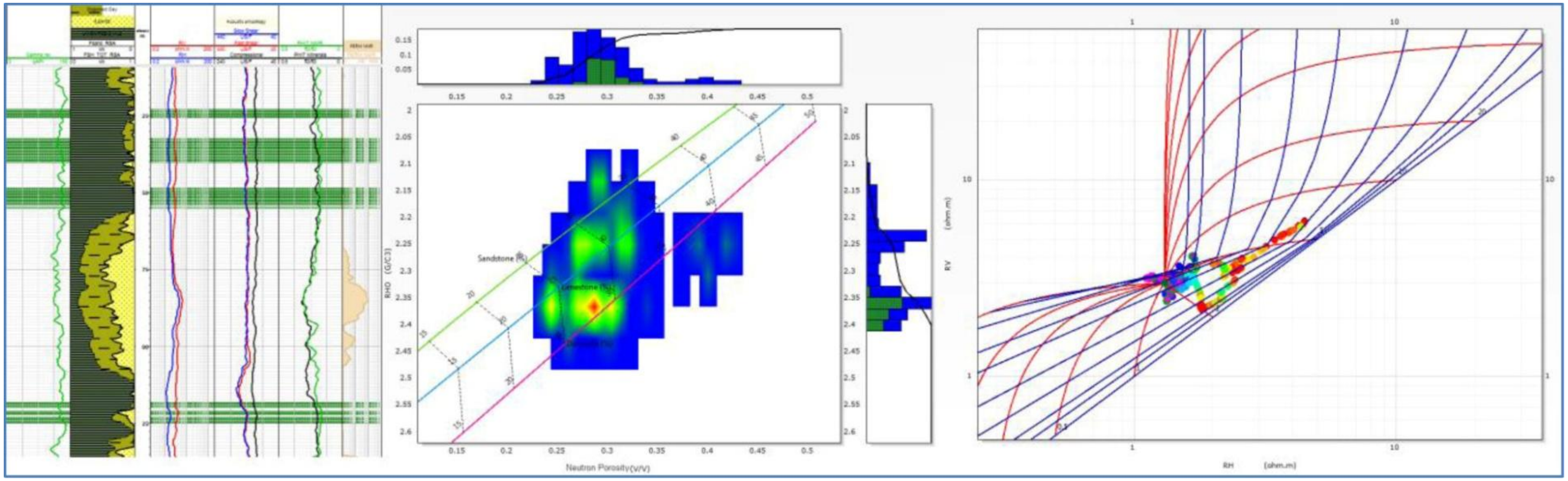

Figure 11. Laminated shale analysis. The neutron-density crossplot identifies the depths of clean shale (depth log plot on the left side is included for visual representation of the high-density values plotting across the shale point). On the right side is the crossplot defining the clay-point properties.

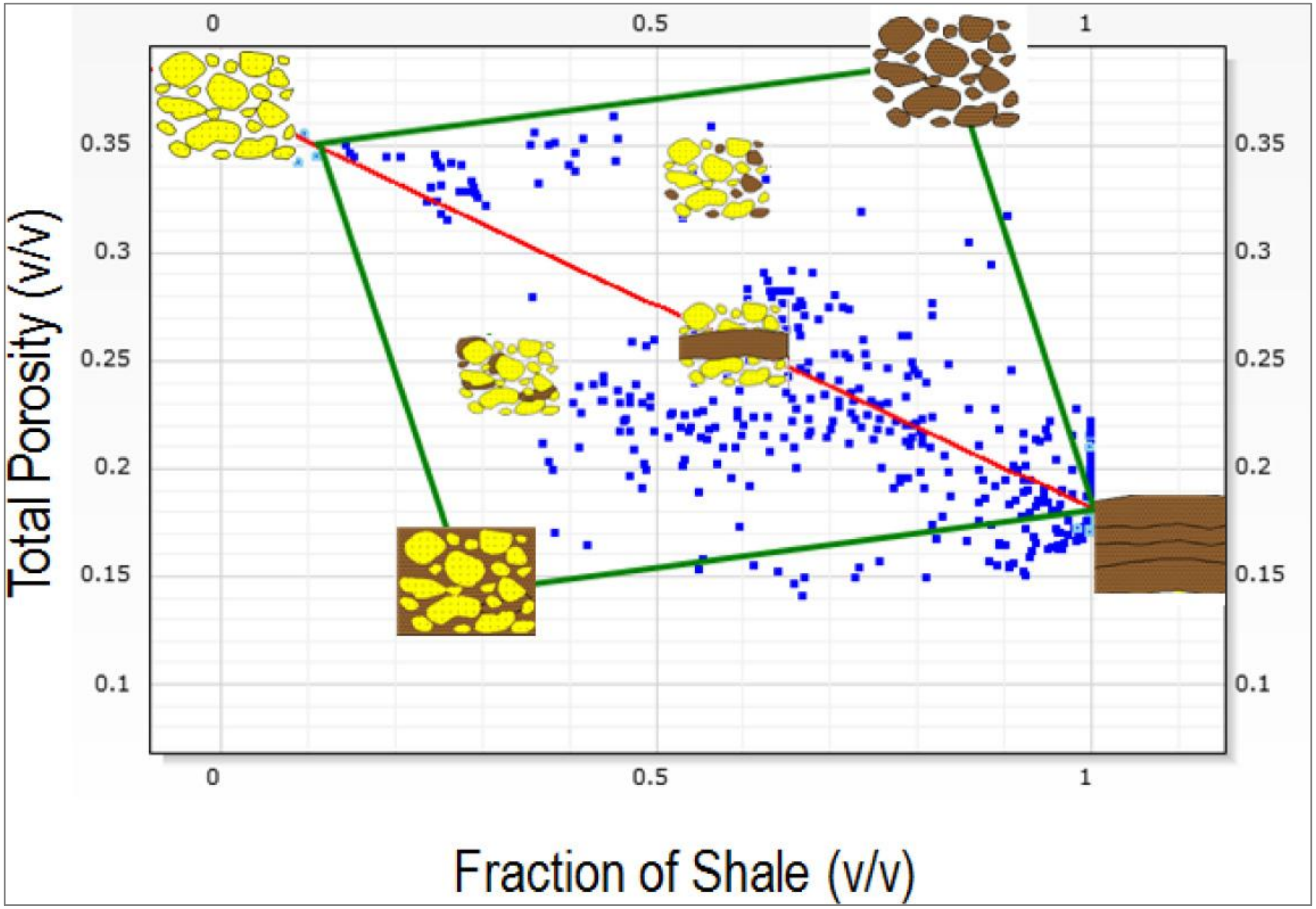

Figure 12. End points definition plot. Total Porosity (matrix corrected) versus Total Shale Volume indicates the presence of laminae of shale and sand with dispersed clay (points plotting below the trend line in red) in addition to structural clay and shale with no sand content.

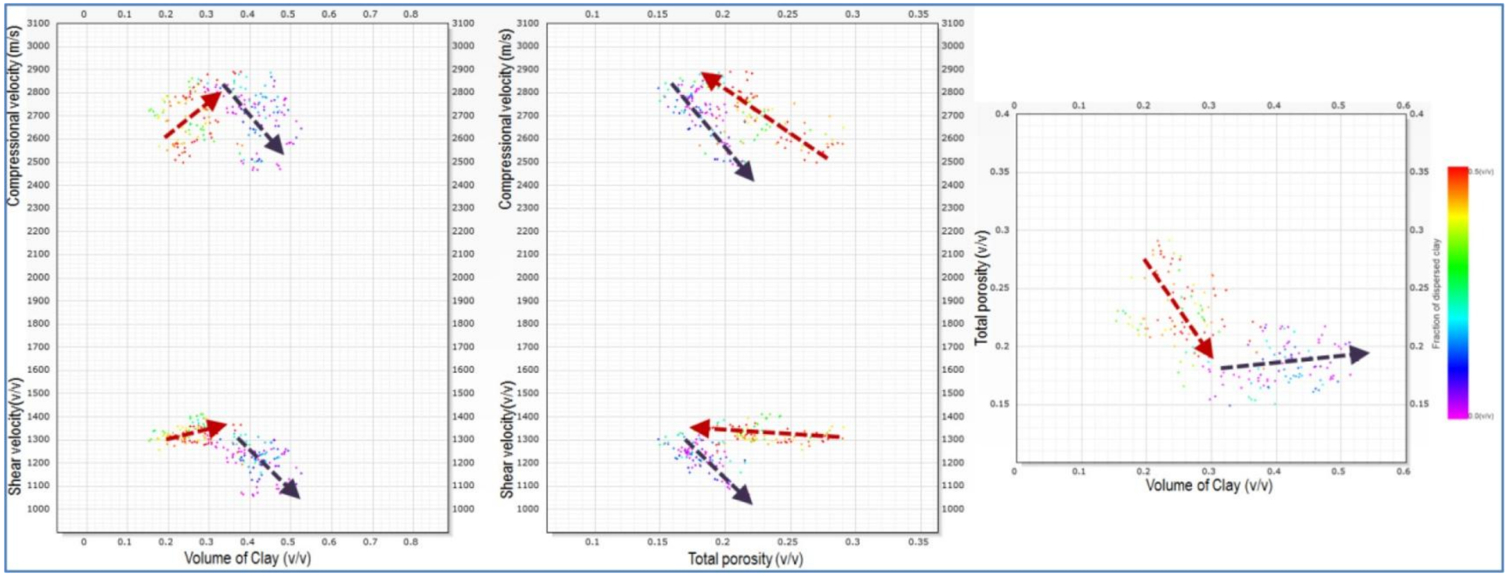

Figure 13. Crossplots describing the sonic-petrophysics relationship across the LRLC reservoir to validate the multiple-shale-fraction effect. Typical trends identified by the arrows confirm the applicability of a dispersed-clay sand and dispersed-quartz shale model and describe the shale-fraction effect. The arrows point from high to low fraction of dispersed clay.

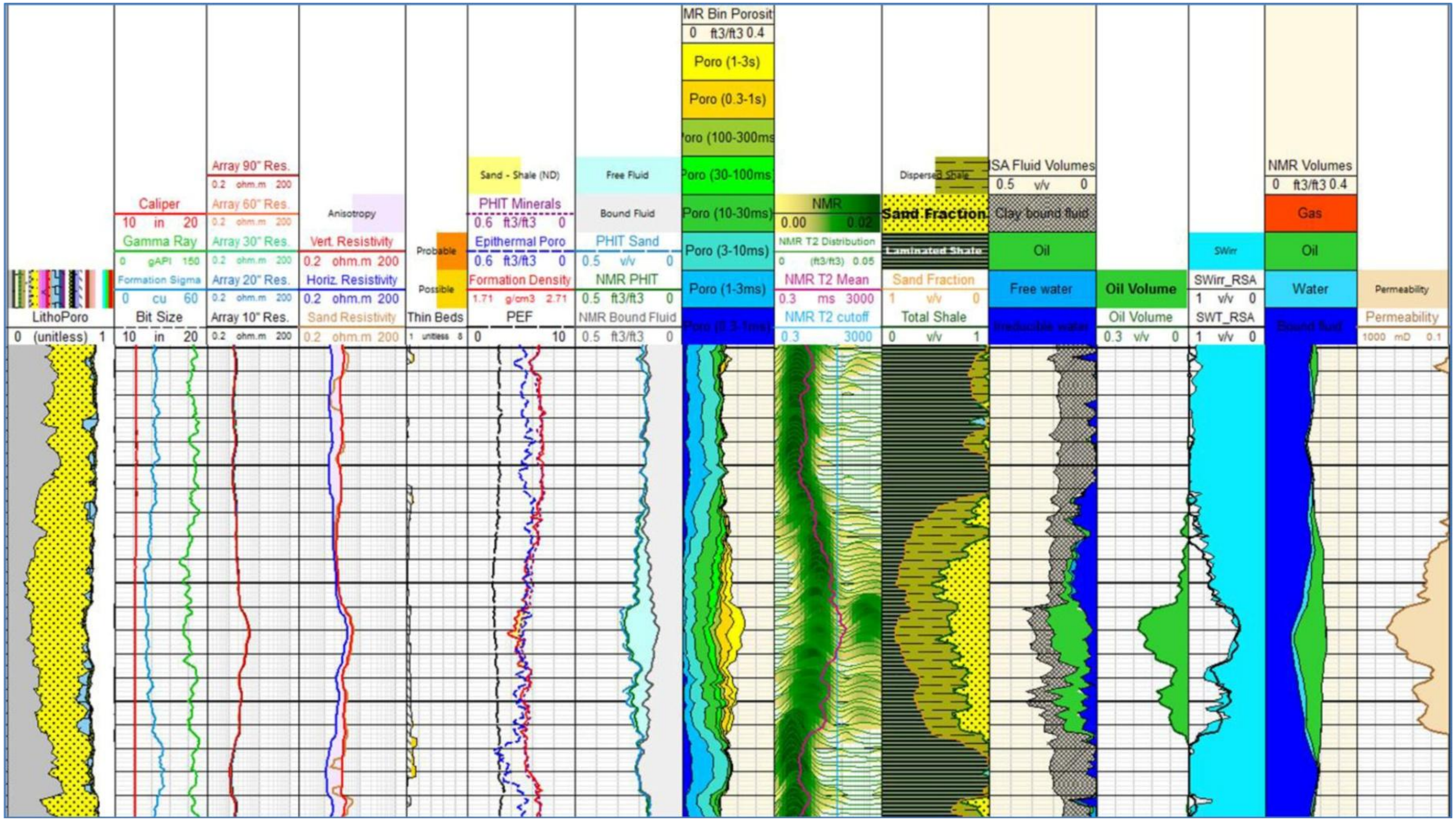

Figure 14. Results of main interpretation across the LRLC pay (top zone in the log plot) and other complex shaly-sand reservoir (bottom ones) – Plot scale is1:200ft MD.