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Combined NMR and conventional log petrophysical evaluation of a sandstone reservoir, offshore Niger Delta, Nigeria

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Abstract

Joint petrophysical analysis using conventional and nuclear magnetic resonance (NMR) logs was conducted for two wells in an offshore field, Niger Delta, Nigeria, using Interactive Petrophysics (IP) software. Delineated reservoir unit comprises of 11 and 5 zones on conventional logs in wells 1 and 2 with 6 and 3 zones on NMR logs in wells 1 and 2. Results show that oil is the predominant fluid type at the delineated depth intervals. Significant difference in the values of computed petrophysical parameters of interest from conventional log analysis only compared with the values from the integration of conventional and NMR logs have been established. The sensitivity of NMR logging tools to fluid contents only in reservoirs has assisted in mitigating the shortcomings of conventional logs, thus leading to fairly more accurate and reasonable estimation of reservoir parameters. Also, If NMR tools were run in the reservoir zones devoid of NMR information, there is high probability of having the same pattern of results in situations where they have similar geological settings.

Keywords: Petrophysics, porosity, permeability, producibility, reservoir, Niger Delta.

Introduction

Recent developments in logging-while-drilling (LWD) and wireline logging technology coupled with the emergence of NMR logging technology, have contributed immensely to the petroleum industry's capability to position wells in reservoirs, evaluate nearby formations, and understand reservoir properties along with the nature of rocks and fluids they contain[1]. Porosity and permeability as the main dominant and challenging attributes in subsurface reservoir characterization. have the greatest impact on reserves and prospects, and consequently on the economy of any exploration project[2,3]. Since these two parameters vary significantly over reservoir volume, sampling is usually done at well locations using different techniques at different scales of observation[4-7]. The correct computation of the pattern and disposition of porosity and permeability is important in achieving successful drilling outcome, and reduction in number of wells necessary to evacuate reservoirs. However, the evaluation of reservoir permeability at prospecting depth is only achievable on cores (which is not always available), or deduced from pressure and flow rate data[8].

Another petrophysical parameter of interest in petroleum geoscience and engineering perspective is the producibility factor, *kH* (*k* is permeability, *H* is the reservoir thickness). Producibility offers a complementary role in conjunction with the more fundamental engineering factors such as pressure, volume, temperature and the geometry of the reservoir. Reservoir evaluation based only on conventional logs for the correct estimation of reservoir producibility is often inadequate due to the irreducible water saturation parameter that is evasive or which requires some approximations and which in most cases are subjective, and might result in inaccurate determination of permeability[9].

One way of improving reservoir assessment is to integrate NMR log with conventional logs to assist in making sound and reliable economic decision in exploration projects. NMR log analysis has been conducted independently[10] as well as in conjunction with traditional log and in-situ direct data[11-13]. When used as a stand-alone logging tool, NMR measurement is able to generate porosity, permeability indicator, comprehensive data on fluid content and volume as well as flushed zone saturation[14]. Moreover, NMR logs is easily differentiated when compared with density and resistivity logs due to the fact that NMR response depends mainly on the type and amount of fluid in reservoir pore spaces and are largely unaffected by formation lithology[15-18]. It has also been shown that lithology, fluid type and formation heterogeneity increase the uncertainty in porosity computation from density log[19-23]. NMR technology has been established as a requisite formation evaluation tool, especially for low-resistivity reservoirs[15, 24-26]. By its ability to differentiate movable from immovable fluids, NMR logs have greatly enabled log analysts in accomplishing better results and satisfactory hydrocarbon volume quantification with greater confidence in relation to conventional resistivity log interpretation[27]. For joint analysis and interpretation, NMR log and deep resistivity data have been integrated to determine whether producible water is in the virgin zone, or whether an interval with high water saturation will accurately delineate water-free hydrocarbon zone[28].

The most productive basin in Nigeria is the Niger Delta which is a conglomerate of several onshore and offshore fields. The onshore field is essentially a sandstone reservoir which makes it possible for conventional logs to resolve many petrophysical challenges. However, the geology of deep offshore which are now the most promising field is more complex and hence requires the integration of higher technologies or techniques to resolve the complexities. In this study, two wells in the P-field, Niger Delta oil province, are evaluated using NMR logs integrated with conventional logs with a view to facilitate accurate prediction of reservoir porosity, permeability and producibility for economic considerations. The specific objectives are to: estimate reservoirs' petrophysical variables using conventional logs and NMR logs acquired in the study area; compare the reservoir permeability and producibility values from conventional logs only with those from the integration of conventional and NMR logs in the area under investigation as a strategy to reduce uncertainty that can adversely affect exploration outcomes.

Geological setting: The Niger Delta oil province is an extensional rift basin situated in the Gulf of Guinea on the passive continental margin close to the western shoreline of Nigeria in west Africa (Figure-1) accessible to Cameroon, Equatorial Guinea and Sao Tome and Principe[29,30]. It belongs to the Tertiary and encloses a region that has subaerial stretch of about 75,000 km^2, a total area of 300,000 km^2, and a sediment fill of about 500,000 km^3 [29] at a depth between 9 – 12 km [31]. It comprises an extensive regressive clastic succession of structures with a maximum thickness of 30,000 to 40,000 ft (9,000 to 12,000m). Sediment deposition in the basin commenced in the late Paleocene/Eocene (Figure-1), with the formation of conduits within the basement horst bands in the northward border of today's delta area.

The structural disposition and strata succession in the Niger Delta is mainly controlled by rates of sediment deposition and subsidence[34-36]. Eustatic sea level fluctuations and weather swings direct the sediment settling rates while the creation and deformation of rock and unequal weight and settlement on compressible shale may have impacted the subsidence[37]. Rock unit is discontinuous in the delta with age from Pliocene in the north to possibly as young as plio-pleistocene in the south. Subsurface layer arrangement of the Niger Delta can be categorized into an uppermost sequence of vast sands and gravels (Benin Formation), which increases inward in the crust over some intermediate strata made up majorly of sand intermingle with some shale layers, thereby forming an intercalation of sandstone and shale (Agbada Formation), deposited under paralic conditions[30,38]. The Akata Formation is the zones beneath the Agbada Formation, and comprises mainly of marine shale, with the connected sandstone units mostly turbidities (Figure-1). The prominent hydrocarbon trapping system in the Niger Delta fields are structural with few stratigraphic traps also present. These include rollover structures and fault closures[39-41]. The principal seal rock in the basin is the intercalated bed of shale enclosed in the Agbada Formation[42, 43].

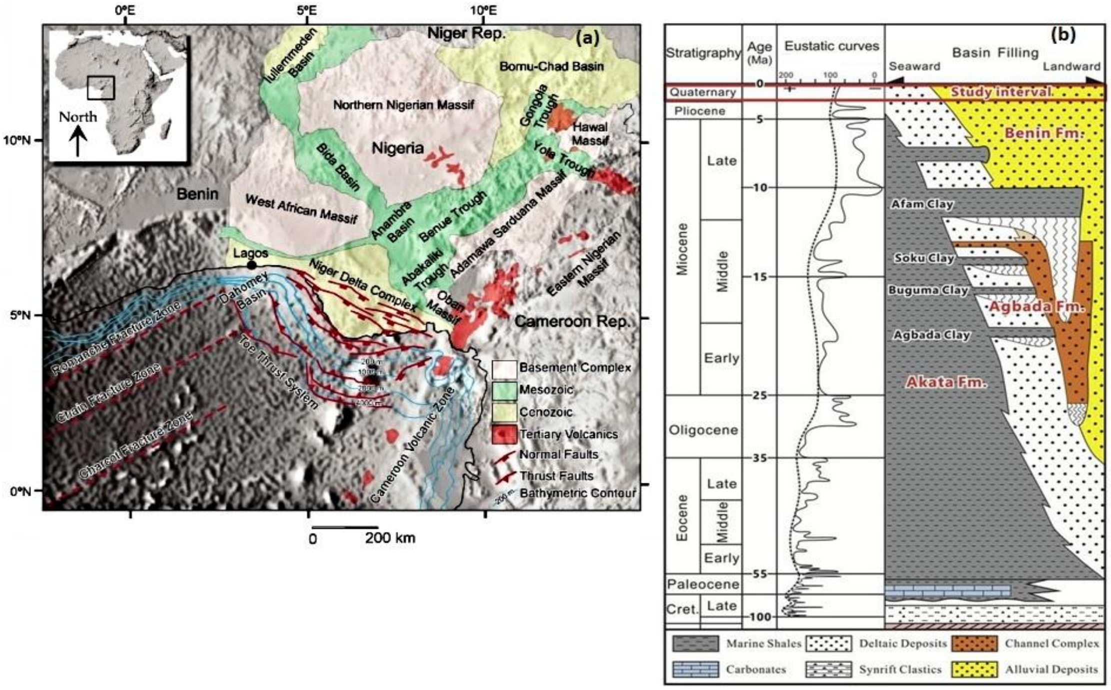

Figure-1: (a) Key Sedimentary Basins and Tectonic attributes of the Niger Delta province showing the Topography and Bathymetry of the region[32]; (b) Schematic representation of the Niger Delta regional stratigraphic configuration showing the Akata, Agbada and Benin Formations (Several modifications have been obtained from the works of several authors[33].

Methodology

The sets of data used in this study were acquired from P-Field located within the western province of the Niger Delta deep offshore. Data sets comprise of conventional logs (gamma ray, resistivity, density, and neutron) and NMR relaxation time, free fluid volume (FFV) and bound fluid volume (BFV) from two wells (Figure-2). The conventional log and NMR log data were uploaded and edited for bad hole and environmental corrections using Interactive Petrophysics (IP) software version 3.4. The software was also utilized in the processing and interpretation of petrophysical data. The reservoir formations of interest were defined and map out through the integrated analysis of lithology, resistivity and porosity logs. Clay volume analysis was done using the gamma ray, resistivity and porosity logs[44] and the resulting curves for each displayed on the same track for easy comparison. The gamma ray log reading in the clean and shaly zones were estimated by adjusting the clean and shaly formation lines in the gamma ray log histogram to reasonable values and these values were used in the estimation of the volume of shale.

Neutron-Density porosity or total porosity (φ_{ND}) was estimated using mean method from Gaymard-Poupon approximation[45]. Effective porosity φ_E was calculated from the total porosity using a combination of neutron and density logs[44] and categorized based on the qualitative evaluation of porosity in reservoir rocks in the Niger Delta accordingly[46]. Due to lack of access to core data, the plot of effective porosity against volume of clay/shale[47] was employed for recognising the type of clay distribution present within the zones of interest in the field under consideration in order to ascertain the water saturation model (Indonesia model) to use[48].

The computation of other petrophysical parameters such as hydrocarbon saturation (S_h); flushed zone water saturation (S_{xo}); residual hydrocarbon saturation (S_{hr}); movable oil saturation (MOS); movable hydrocarbon Index (MHI); bulk volume water (BVW) was achieved using formulae given by Asquith and Gibson (1982). NMR total porosity (φ_{NMR}) gives the sum of FFV and BFV. Irreducible water saturation from conventional logs (S_{wir_CONV}) and Irreducible water saturation using the integration of NMR and conventional logs ($S_{wir\_CONV\_NMR}$) were determined using Equations (1) and (2) respectively[49]:

$$S_{wir\_CONV} = \left(\frac{1}{200 \times \varphi_T^2} \right)^{0.5} \quad (1)$$

$$S_{wir\_CONV\_NMR} = \frac{\varphi_T - \varphi_{NMR}}{\varphi_T} \quad (2)$$

$\varphi_{ND}(\varphi_T)$ is the total porosity calculated from the conventional method and (φ_{NMR}) is the porosity from NMR. The results from Equations (1) and (2) are directly incorporated into permeability *k* and producibility *kH*. *k* was estimated with irreducible water saturation from the conventional only (S_{wir_CONV}) as well as from the irreducible water saturation from the integration of NMR and conventional log respectively ($S_{wir\_CONV\_NMR}$), using in Equations (3):

$$k^{0.5} = 250 \times \frac{\varphi^3}{S_{wir}} \quad (3)$$

$$\text{Producibility} = kH \quad (4)$$

kH is a function of build-up and drawn down tests and is an important variable in the flow potential of a well.

Results and Discussion

Conventional and NMR log data were integrated using the same software IP 3.4 version to obtain digital values from the analog plots. The interpreted porosity and water saturation for the two (wells 1 and 2) are displayed in Figures-3 and 4 respectively. The summary of the petrophysical analysis for conventional and NMR analyses of well 1 are presented in Table-1 and Table-2 respectively while those for well 2 are displayed in Table-3 and Table-4 respectively.

Altogether the acquired log data at the P-field, offshore Niger Delta has eleven (11) and five (5) hydrocarbon promising zones on conventional logs for Well 1 and Well 2 respectively. While on NMR logs, data acquisition due to cost implication only covers six (6) and three (3) promising zones in well 1 and Well 2 respectively. As summarized on Table-1, 4, net reservoir depth in the two wells from the suites of log data are at close ranges; 6285-12,319 ft and 6290-11779 ft in conventional logs and NMR logs respectively. Overall estimated porosity range (15-40%) across the wells indicate that the sand reservoir in the field has good to excellent porosity[44]. Also the ranges of other petrophysical parameters viz: S_w (5–38%); S_h (69-92%); S_{hr} (21 -40%); MHI (0.13-0.39); MOS (0.48-0.54) all reveals that this field is promising for exploration project.

Estimated values of porosity **Ø** (0.153-0.342) and water saturation S_w (0.127-0.255) from conventional log analysis are a little higher for Well 1 than those from the integrated analysis, (0.138-0.266) and 0.240-0.310) respectively. For Well 2, **Ø** values (0.262-0.404) from conventional method are also higher than those predicted from integrated technique (0.259-0.280). But the reverse is the case for S_w: conventional method; 0.053 - 0.153 and integrated approach; 0.244-0.377.

Predicted irreducible water saturation S_{wir} values for the wells are significantly higher for integrated approach (Well 1: 0.128 - 0.477 and Well 2: 0.012-0.353) than the predicted results from conventional method only (Well 1: 0.065-0.146 and Well 2: 0.055-0.085). Generally, the upper limit values for permeability *k* are quite higher for conventional analysis – 23615 mD for Well 1 and – 89056 mD for Well 2 than the integrated analysis - 20229 mD for Well 1 and – 7345 mD for Well 2. kH explicitly follow the same trend as k. kH range is 5555–3306100 mDft for Well 1 and 75384–3377920 mDft for Well 2 from conventional approach. But with the integration of NMR and conventional methods, kH varies from 247114-4450380 mDft and 48944 - 998920 mDft for Well 1 and Well 2 respectively. Hence, the trend of results in the various hydrocarbon facies in the field under study establishes an overestimation of producibility using the conventional method only in comparison with the analysis from the integration of NMR and conventional logs. The sensitivity of NMR tools to the fluid contents only in reservoirs has assisted in mitigating the shortcomings of conventional logs, thus leading to a more accurate estimation of reservoir producibility. Also, If NMR tools were run in the reservoir zones devoid of NMR information, there is high probability of having the same pattern of results in situations where they have similar geological settings.

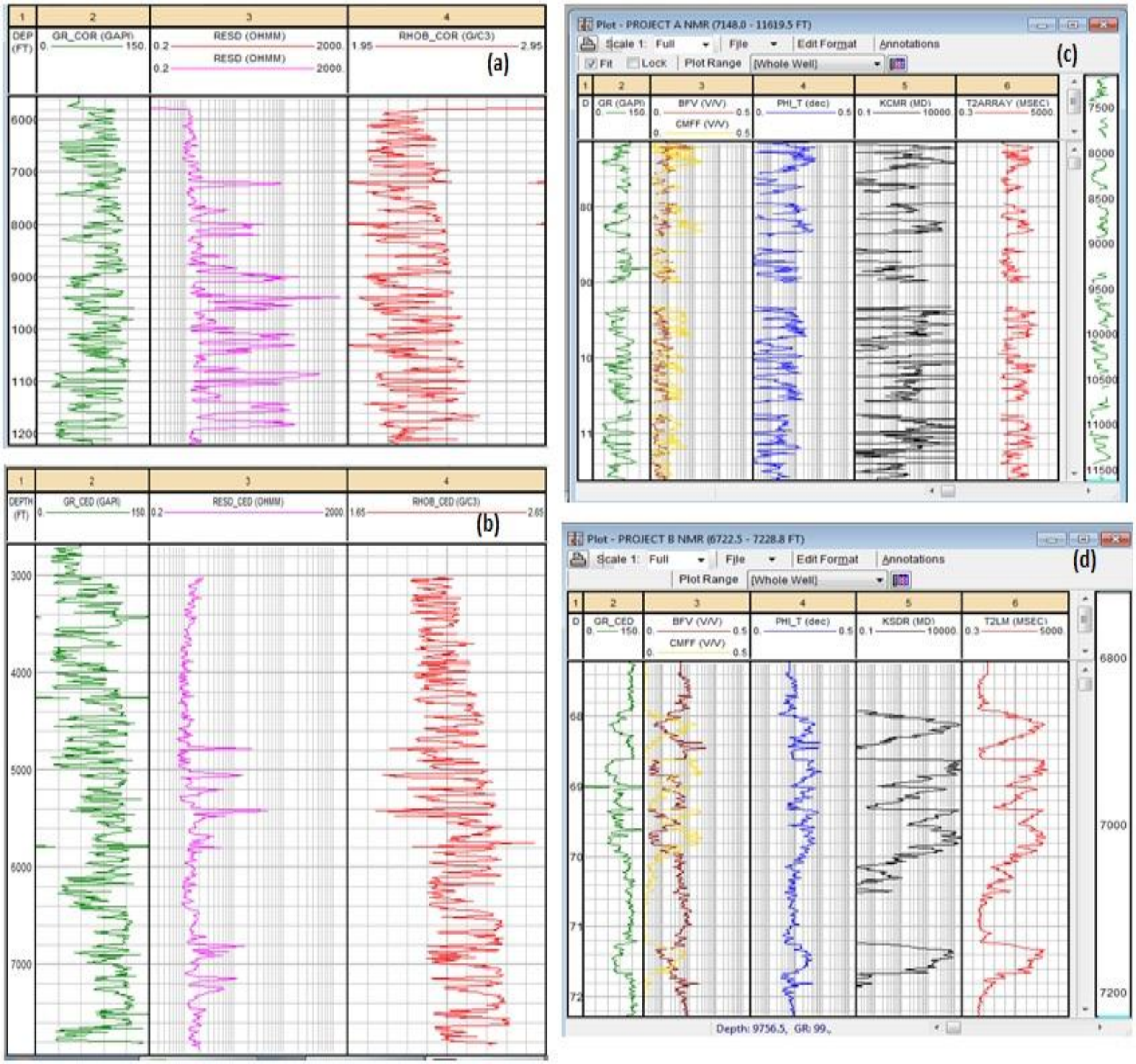

Figure-2: (a) Uploaded depth track, gamma ray, resistivity and bulk density logs for Well 1; (b) Uploaded depth track, gamma ray, resistivity and density logs for well 2; (c) Uploaded NMR log for well 1; (d) Uploaded NMR log for well 2.

Table-1: Summary of computed petrophysical parameters for Well 1 using conventional log analysis.

Zone	Top (ft)	Base (ft)	ϕ (%)	F	S_w (%)	S_h (%)	V_{cl} (%)	H (ft)	S_{wir} (%)	k (mD)	kH (mDft)	BVW	S_{xo} (%)	MOS (%)	MHI	S_{hr} (%)
1	6285	6519	0.334	8.99	0.239	0.761	0.177	234	0.067	19174	4486716	0.080	0.751	0.512	0.318	0.249
2	7382	7522	0.342	8.53	0.179	0.821	0.138	140	0.065	23615	3306100	0.061	0.709	0.530	0.253	0.291
3	8005	8273	0.295	11.48	0.165	0.835	0.117	268	0.076	7189	1926652	0.049	0.697	0.532	0.237	0.303
4	8929	9213	0.276	13.15	0.142	0.858	0.103	284	0.081	4185	1188540	0.039	0.677	0.535	0.210	0.323
5	9480	9845	0.256	15.21	0.078	0.922	0.036	365	0.087	2335	852275	0.020	0.600	0.522	0.130	0.400
6	10083	10280	0.237	17.77	0.077	0.923	0.033	197	0.094	1253	246841	0.018	0.598	0.522	0.128	0.402
7	10125	10359	0.255	15.40	0.127	0.874	0.084	234	0.088	2221	519714	0.032	0.661	0.535	0.191	0.339
8	10683	10871	0.186	29.00	0.206	0.794	0.100	188	0.120	177	33276	0.038	0.729	0.523	0.282	0.271
9	11498	11599	0.160	38.87	0.197	0.803	0.075	101	0.139	55	5555	0.032	0.723	0.526	0.273	0.277
10	11628	11805	0.153	42.50	0.255	0.745	0.088	177	0.146	38	6726	0.039	0.761	0.506	0.335	0.239
11	12203	12319	0.261	14.64	0.207	0.793	0.175	116	0.086	2725	316100	0.054	0.730	0.523	0.284	0.270

Table-2: Summary of computed petrophysical parameters of Well 1 using integration of conventional and NMR log analyses.

Zone	Top (ft)	Base (ft)	H (ft)	ϕ (%)	ϕ (%)	S_{wir} (%)	k (mD)	kH (mDft)	S_w (%)	S_h (%)	BVW	S_{xo} (%)	MOS (%)	MHI	S_{hr} (%)
1	6290	6510	220	0.342	0.266	0.223	20229	4450380	0.25	0.750	0.086	0.7579	0.508	0.330	0.242
2	7432	7653	221	0.295	0.246	0.166	14910	3295110	0.24	0.760	0.0708	0.7517	0.512	0.319	0.248
3	9480	9903	423	0.276	0.208	0.246	4552	1925496	0.24	0.760	0.066	0.7511	0.512	0.318	0.249
4	10093	10543	450	0.256	0.190	0.259	2648	1191600	0.30	0.696	0.078	0.7881	0.484	0.386	0.212
5	10924	11466	542	0.186	0.162	0.128	1574	853108	0.22	0.778	0.041	0.7401	0.518	0.300	0.260
6	11513	11779	266	0.264	0.138	0.477	929	247114	0.31	0.691	0.0815	0.791	0.482	0.391	0.209

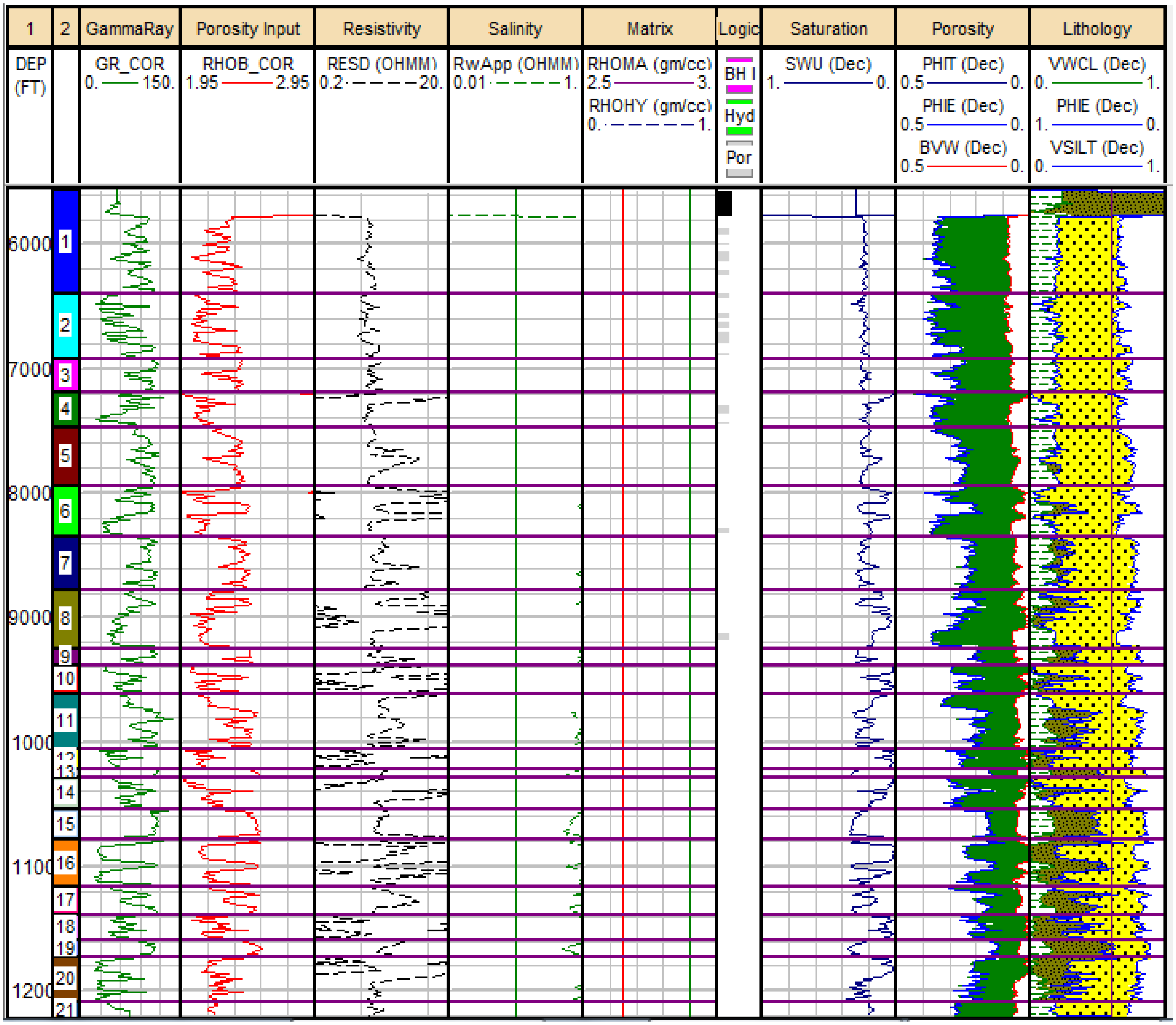

Figure-3: Porosity and Water Saturation Plot from Interactive Petrophysics software hydrocarbon zones for Well 1.

Table-3: Summary of computed petrophysical parameters for Well 2 using convectional log analysis.

Zone	Top (ft)	Base (ft)	ϕ (%)	F	S_w (%)	S_h (%)	V_{cl} (%)	H (ft)	S_{wir} (%)	k (mD)	kH (mDft)	BVW	S_{xo} (%)	MOS	MHI	S_{hr} (%)
1	3689	3716	0.262	14.55	0.153	0.847	0.417	27	0.085	2792	75384	0.040	0.687	0.534	0.223	0.313
2	3982	4013	0.404	6.12	0.053	0.947	0.102	31	0.055	89056	2760736	0.021	0.556	0.503	0.095	0.445
3	6432	6476	0.379	6.96	0.084	0.916	0.157	44	0.059	53439	2351316	0.032	0.609	0.525	0.138	0.391
4	7823	7892	0.349	8.20	0.081	0.919	0.224	69	0.064	27638	1907022	0.028	0.604	0.524	0.133	0.396
5	7924	7982	0.383	6.81	0.079	0.921	0.148	58	0.058	58240	3377920	0.030	0.602	0.523	0.131	0.398

Table-4: Summary of computed petrophysical parameters for well 2 using integration of convectional log and NMR Analyses.

one	Top (ft)	Base (ft)	H (ft)	ϕ (%)	ϕ (%)	S_{wir} (%)	k (mD)	kH (mDft)	Sw (%)	S_h (%)	BVW	S_{xo} (%)	MOS	MHI	S_{hr} (%)
1	5084	5107	23	0.280	0.274	0.012	2128	48944	0.325	0.675	0.090	0.799	0.474	0.407	0.201
2	6438	6574	136	0.280	0.223	0.203	7345	998920	0.244	0.756	0.068	0.754	0.510	0.324	0.246
3	7831	7866	35	0.259	0.168	0.353	1518	53130	0.379	0.621	0.098	0.823	0.445	0.460	0.176

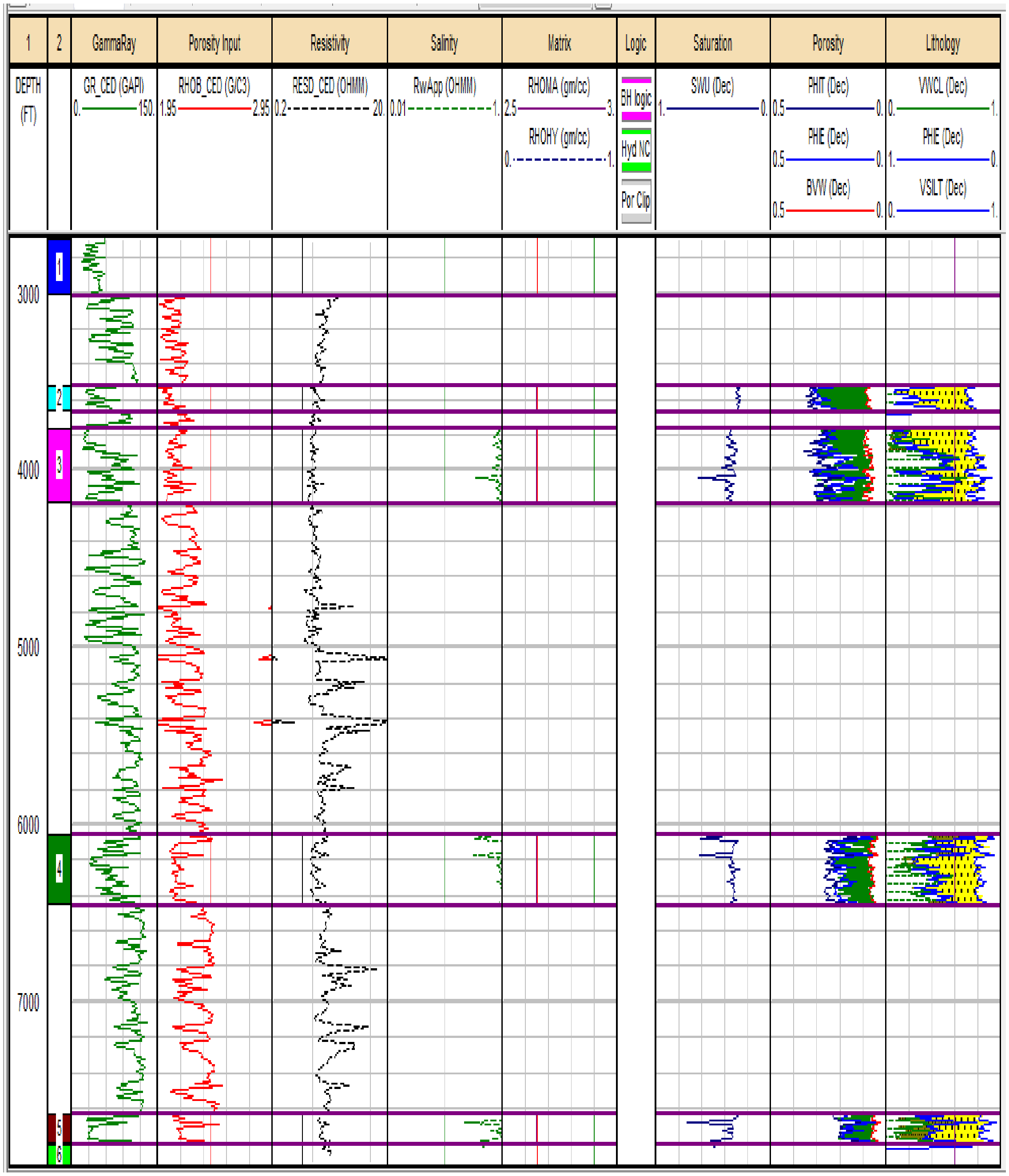

Figure-4: Porosity and Water Saturation Plot from Interactive Petrophysics software around hydrocarbon zones for Well 2.

Conclusion

The results of the petrophysical evaluation of the available two wells in P-field, offshore Niger Delta have been used to determine the productive depth interval of hydrocarbon zones they contain. Well 1 has six hydrocarbon zones while well 2 has three hydrocarbon zones with overall depth intervals 6285 – 12319 ft. Estimated values of petrophysical parameters show that the two wells in this field are promising for exploration project because of their good to excellent porosity values (15 – 40%), high hydrocarbon saturation (69–92%), low water saturation (5–38%), low residual hydrocarbon saturation (0.18 – 0.40%), high movable oil saturation (0.48–0.54), moderate to high permeability values, and favourable values for moveable hydrocarbon index. Though there are overlap in the range of values for the product of reservoir permeability k and thickness H (producibility), there is an apparent overestimation of producibility values with conventional logs in comparison to NMR logs. Notably, the upper limit values for permeability k are quite higher for conventional analysis (23615 mD for Well 1 and 89056 mD for Well 2) than the integrated analysis (20229 mD for Well 1 and 7345 mD for Well 2). kH explicitly follow the same trend as k. kH range is 5555-3306100 for Well 1 and 75384 - 3377920 for Well 2 from conventional approach. But with the integration of NMR and conventional methods, kH varies from 247114-4450380 mDft and 48944–998920 mDft for Well 1 and Well 2 respectively. Therefore, the integration of NMR and conventional log analysis for petrophysical characterization has proven to be a valuable and effective approach in improving the possibility of achieving more reliable results for economic decision. Thus producibility prediction can be extended to other wells within the same field or wells in nearby field that do not have NMR data for as long as they share similar geological setting. This shows an overestimation of producibility using the conventional method only in comparison with the analysis from the integration of NMR and conventional logs. This is probably due to the sensitivity of NMR tools to the fluid contents only in the reservoir, thereby resulting in more reasonably accurate estimation of reservoir producibility.

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