Reservoir Characterization of Gandhar Pay Sands by integrating NMR log data with conventional open hole logs – A Case Study.

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Summary

Gandhar field of Ankleshwar Asset is consisting of multilayered sandstone reservoir of Eocene age. The field is producing from fourteen different sand units of highly heterogeneous in nature. Presently the field is in tertiary recovery stage of production and IOR / EOR scheme is under implementation. Efforts are on from asset team to improve the recovery factor from its current average value of 39. But severe heterogeneity and complexities in the reservoir properties are the main hindrance to achieve this goal. Sometimes it is difficult to plan a proper exploitation strategy to increase the Producibility for some of the sand units.

Formation evaluation of this clastic reservoir has been done so far, with the help of available conventional open hole logs. These logs are measuring Electrical resistivity, Nuclear and Acoustic properties of the formation. They can provide information like Lithology, Porosity, Clay content, Fluid saturation and Net Pay thickness of the formation. But computed fluid saturation (S_w) many times mismatches with the production testing result and does not describe the reservoir behaviour completely. Presence of heterogeneity in micro scale (local) play a major role in determining reservoir producibility and the same in macro scale (field- wise) limit the reservoir extent. Conventional open hole log can identify a reservoir but can not say about the presence of free porosity in it and the connectivity between the free pores. These two are the major factors which determine the producibility of the reservoir.

Integration of state of the art NMR technology with the Conventional logs help to evaluate the Producibility of such heterogeneous formation. It helps to evaluate the reservoir rock properties and fluid properties to do a complete static reservoir characterization job. NMR log data helps to ascertain about the Reservoir quality by computing the ratios of free fluid volume to bound fluid volume present in a particular flow unit. Flow zone index is a measure of reservoir producibility can also be computed from NMR log derived data. It is defined as the ratio of Rock volume open to flow to total area wetted. These reservoir descriptions will help in better Reservoir Management and to plan proper exploitation strategies for each sand (flow) unit so that present R/P ratio can be reduced through better producibility.

NMR log is recorded in a very limited number of wells of Gandhar field against the major pay sands. Two such wells are G# I and G#II. They were taken for present study and discussion in this article. The case study shows NMR log data explains the production performance and the reservoir behavior of the sand units in a better manner where conventional open hole log fails. Reservoir quality of each sand units were evaluated in the first example of the study and presented in Table: 1 as Rock type summary. The computed values of the static reservoir properties are then validated with the data obtained from core plug analysis and actual formation testing results for determining the accuracy of the work.

Second example shows the reservoir producibility by analyzing the result of magnetic resonance fluid characterization method, which confirms with the production testing result. A standard workflow is also designed which suits the appropriate formation evaluation of the sand units by data integration process.

Introduction

Gandhar oil field is located in Jambusar-Broach block of South Cambay basin, 37 Km NW of Bharuch town. The field was discovered in 1983, and came into production in 1986.Production is from multilayered sandstone reservoir, stratigraphically known as Hazad sands of Eocene age. So far, 560 no. of wells were drilled here and the field is in mature stage of production. Water injection was started for pressure maintenance in 1991 and currently IOR/EOR scheme is under implementation to improve the recovery efficiency of the reservoir.

Fourteen different sand units were marked in the open hole logs from which hydrocarbon production is taking place, depending upon their development and character near the wellbore. These sands are deposited in a fluvial Deltaic geological setting and highly heterogeneous in character.

Sometimes heterogeneity is so severe that rock properties and fluid properties may change in proximity well. This micro scale heterogeneity affects the reservoir production behavior and performance. Standard formation evaluation from conventional logs can identify the hydrocarbon bearing interval correctly but often fails to answer many producibility issues. To find the answer of fluid mobility in a reservoir often a formation testing job was planned in earlier days using Drill stem testing or Selective formation tester device. New technology NMR wireline tools can overcome this time consuming testing experiment by providing the important reservoir parameters like permeability, pore radii, bound / free fluid volume, viscosity etc. Moreover NMR data acquisition is continuous in a static reservoir condition without creating any pressure differential or drawdown in the borehole. The valuable data obtained from successful recording of NMR log and its subsequent analysis helps to characterize the reservoir in static condition. Knowledge of such reservoir properties will help to plan & execute the exploitation scheme. Integration of NMR result with conventional log data answers the reservoir performance by evaluating e.g. rock characteristics and fluid property.

The present work deals with the evaluation of NMR log data for two wells G#I and G#II in tandem with the conventional logs. The work clearly shows how NMR can more reliably answer the production performance of the pay sands over conventional logs.

Theory

The reservoir characteristics interpreted as part of formation evaluation can be classified into following broad categories:

Rock characteristics- Lithology, Litho unit thickness, Clay type and content, Porosity (storage capacity), Permeability, (flow potential), Pore size and its distribution.

Fluid characteristics: Fluid content (S_w), Fluid type, Bound fluid volume (BFV), Free fluid volume (FFV),Viscosity (μ), and Residual oil saturation (ROS).

Conventional open hole log interpretation can provide the answer of different litho-volumes (quartz, clay etc.), and its thickness, total and effective porosity, but cannot address the issue of free fluid porosity, permeability (flow capacity) and pore radii. Similarly formation evaluation from standard log data set can work out the fluid saturation (S_w) and fluid type but fails to answer the formation fluid mobility/producibility issues.

In NMR logging technology, hydrogen nuclei of the formation fluid is forced to spin and then monitor the rate at which they recover stability. The resulting measurements hold important clues relating to the reservoir rock and fluid parameters.

The time taken by the hydrogen nuclei of the formation fluid to recover and become stable is called Relaxation time (T_2). This relaxation time gives an idea about the pore sizes, and the amount of total porosity which is Lithology independent. T_2 distribution function is analogous to pore size distribution. It measures the bulk properties of the rock and presented as a surface to volume ratio (S/V) of the pores. The area under the T_2 distribution curve measures total porosity of the formation. Large relaxation time indicates the presence of large pore size i.e. macro pores and vice versa. Presence of lighter phase fluid i.e. hydrocarbon also prolongs the relaxation time (T_2) due to its multi molecular composition compare to water molecule. New generation NMR tool can do the in situ fluid characterization in stationery as well as in continuous mode.

In the first step of the work, standard formation evaluation technique was followed by using the Conventional Open hole logs. Each sand units of Gandhar field were identified and marked over the open hole logs and their individual thickness (h) was noted. Average porosity Φ of each sand unit was computed from density neutron logs. Fluid content of each sand unit (S_w) was then computed by using Shaly- Sand model.

In the next step of work, NMR log data was taken into account. Total NMR porosity, free fluid porosity, permeability and T_2 distribution log mean was noted corresponding to each sand units. Mean hydraulic radius (MHR) is computed as a measure of fluid mobility for each sand units using the relationship –

$$MHR = (K / \Phi)^{1/2}$$

Mean hydraulic radius is a measure of reservoir quality and having the dimension of length. The data so analyzed integrating NMR and conventional logs are presented in Table-1 as Rock type summary. The computed result is validated with formation testing data obtained from pump out formation testing device and conventional core plug analysis and found to be correlatable.

Fluid typing was done in new generation NMR tools in MRF station mode. This uses the actual relaxation

time (T_2) distribution curve and applies three different kind of relaxation mode e.g. surface relaxation for water wet rock, bulk relaxation if oil is present and diffusion relaxation component, if gas is present.

Measured T_2- distribution curve is fitted with a modeled curve; build with known input fluid parameters. When the curves were best fit i.e. the coefficient of regression is least then the fluid parameters are established. Similar exercise has been done in Well no: G#II at the stationary depth of XX57.0 against Sand unit -11. The results are shown in Fig -7.

Production testing vis a vis Log analysis results for three objects in Well no: G-I and three other objects in Well no: G-II were discussed in the examples below. A suitable work flow is designed for enhance formation evaluation of this heterogeneous clastic reservoir as a part of the work and incorporated.

Case Study- I

Well: G# 1 Rock typing and Flow Unit Characteristics.

The well was drilled in the year 1999 as an exploratory well with the objective to achieve production from Sand unit -6. The well is located in the main Gandhar field and all the major sand units were developed as seen in the open hole logs. NMR porosity and permeability values are taken against each sand units marked on the open hole logs. Reservoir Characteristics of each sand unit is computed and presented in Table: 1 as Rock type summary. Table shows Sand -3 and Sand -8 are having poor flow characteristics while Sand -9 is having the best flow characteristic among all the sand units. Sand -5 is highly heterogeneous in character. It is showing a permeability variation from 10 to 200 md. Weighted average permeability of this sand is taken as 30 md for computation of Reservoir Quality Index (Refer Table – 1) Presence of high permeability streak in Sand – 5 is confirmed from formation testing data (Using a wireline pump out device) and water injection break through in this layer.

Three objects were identified in this well for production testing on the basis of conventional log analysis and regional geological data. Standard formation evaluation using conventional open hole log shows R_t is 5.0 ohm-m , Φ_e is 0.195 p.u. and S_w is 68 % against the lower part of sand unit -6 (known as 6A) identified as Object –I (Refer Fig.-1) .

Similarly, standard open hole log response against upper part of sand unit 6 (known as 6B) shows R_t is 3.5 ohm- m , Φ_e is 0.22 and S_w is 58 % identified as Object –II for production testing. During production testing, Object – I has produced water with little amount of gas whereas water influx is seen from Object- II.

Table 1: Rock type summary of Gandhaar Pay Sands

Rock Type	Gross Thickness (h) in	Porosity Range (Φ) in P.U	Permeability(k) Range in md (Weighted Mean Value)	Reservoir Quality Index(k / Φ)$^{1/2}$	Fluid mobility in md/cp obtained from Formation testing device	Pore Throat Category	Pore Throat Radius experimentally obtained from Core data
Sand 0	1.0	0.24				Micro	
Sand 1	4.0	0.15–0.25				Micro to Meso	
Sand 2	6.0	0.185–0.255	10-20	7.3—8.9	112	Meso to Macro	Micro toMeso
Sand 3	7.0	0.12-0.18	0.01	Negligible	-	Micro	Micro
Sand 4	5.7	0.23	0.6	1.8	0.4	Mostly Micro	Meso
Sand 5	7.8	0.17-0.225	10 -200 (30)	13	200	Mostly Macro	Micro to Meso
Sand 6	10.5	0.12-0.195	15	11.5-8.77	12	Meso	Meso
Sand 7	2.0	0.19-0.3	0.25	1.2	-	Micro	Not Available
Sand 8	2.5	0.28	0.01	Negligible	-	Micro	Micro
Sand 9	5.0	0.205-0.225	100 -2000 (700)	58.4-55.8	1576	Macro	Micro
Sand 10	3.5	0.13-0.27	20	12.4-8.6	-	Meso	Not Available
Sand 11	7.0	0.16-0.23	10 -90 (50)	17.7-14.7	18	Meso	Micro to Meso

Micro Pores < 1μ (Micron)
Meso Pores > 1μ < 10 μ
Macro Pores > 10 μ
Assumption: Pore throat radii / Pore Radii = 1 (Same)

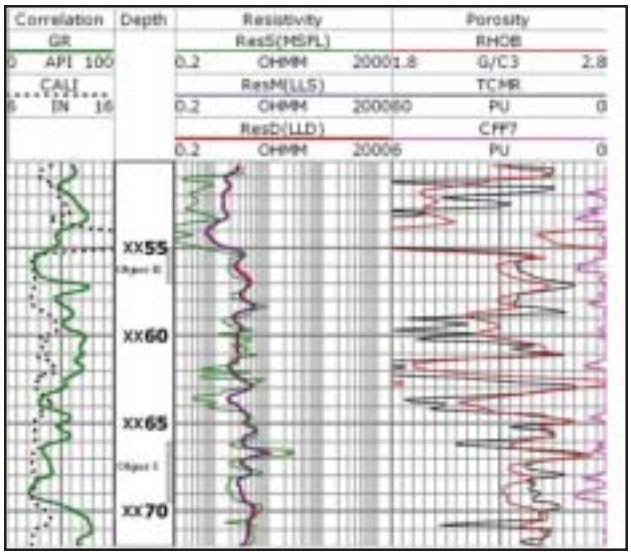


Fig. 1: Standard Resistivity log response against Object-I and Object–II of Well No: G–I

NMR log data is then integrated with the above formation evaluation result. CMR-200 * log response against the Sand -6 indicates presence of Macro to Meso (Large to medium size) pores are more in Sand -6A as compared to Sand -6B, assuming pore radii are same as pore throat radii.

Reservoir Quality Index of the sand units are computed from K-Φrelationship also indicate Sand -6A is having better fluid mobility characteristic (Refer Fig: 2).

Fluid typing was not attempted because the facility was not available in CMR-200. However longer relaxation time in T_2 distribution is noticed in the interval XX67.5 – XX68.5 m, confirming the presence of meso to macro pores

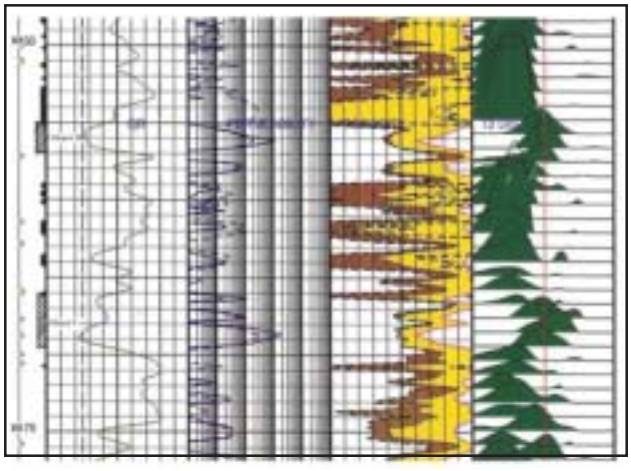


Fig. 2: NMR Log Response against Object-I and Object – II of Well No. G-I

in sand unit -6A. Free fluid porosity in this 1m interval is around 14% v/v, which is sufficient for the fluid to move. Relaxation time (T_2 distribution) is not so prolonged against sand unit 6 so that presence of any hydrocarbon can be deciphered. In case of Sand 6B (Object-II), optimistic S_w is due to the high $\hat{0}_e$ value obtained from conventional density- neutron porosity log and not due to the occurrence of hydrocarbon.. This porosity is due to clay bound and capillary bound water as confirmed by NMR log in this interval.

Open hole log analysis show R_t is 4.3 ohm -m, Φ_e is 0.18 p.u. and Sw is 61 % against upper part of sand unit-11 identified as Object –III for production testing (Refer Fig.-3). On testing this object, it has produced Oil and Gas (Q_o – 86 m^3 / day) through 16/64" choke commensurate with the log analysis result. NMR log data against the Sand -11 shows the presence of meso pores (medium size) and good to moderate permeability from bottom to top of the unit.

T_2 distribution indicates prolonged relaxation time component in the interval XX86.0 – XX88.0 m,confirming the presence of lighter phase fluid (hydrocarbon). NMR free fluid porosity is 10 to 12 % v/v and moderate permeability value indicates that the free pores are mostly connected. Therefore NMR data also suffice the production behavior of this sand unit (Refer Fig: 4). Presently the well is producing 31 m^3 / day of oil from the Sand – 11 (Object -III).

Case Study -2

Well No : G-II. Producibilty Analysis.

Well G-II was drilled in year 2004 as an exploratory well. The well is located at the north of main

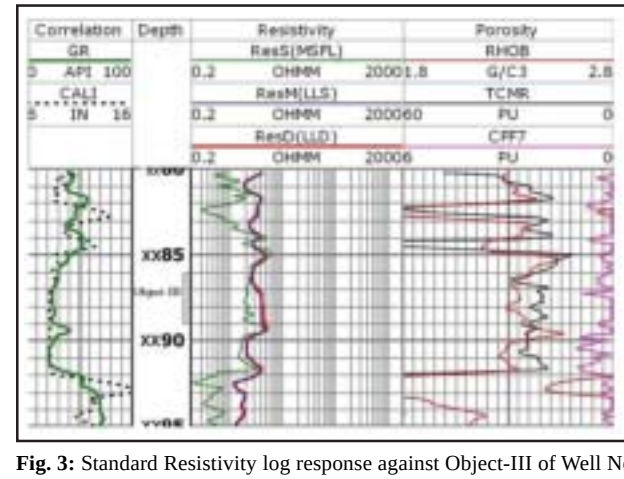


Fig. 3: Standard Resistivity log response against Object-III of Well No. G-I

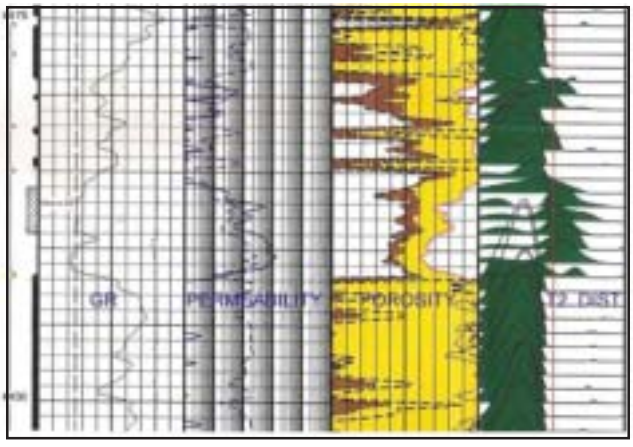


Fig. 4: NMR log response against Object – III of Well no: G - I.

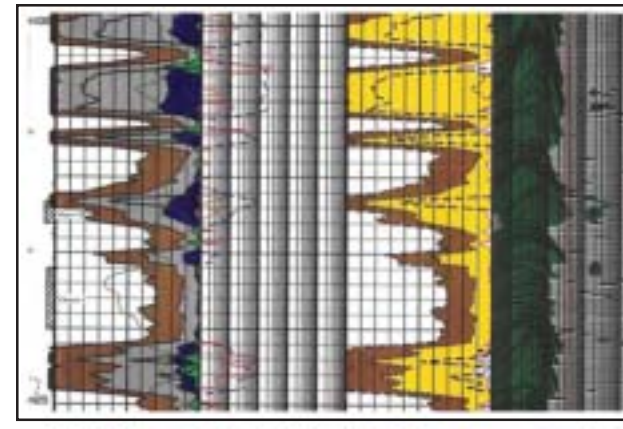


Fig: 5 NMR log response against Object-I and Object-II of the Well no: G-II.

Gandhar field. Open hole log analysis shows only Sand -6 and Sand -11 are developed in this well. The remaining sands are highly silty in nature or completely shaled out. Three Objects were identified in this well for production testing on the basis of standard log evaluation and regional geological data. Out of the three Objects tested, two were in Sand -6 (Sand -6A and Sand -6B) and remaining Object was against Sand -11. Formation evaluation from conventional open hole log indicates R_t is 8.0 ohm-m , $\hat{0}_e$ is 0.3 p.u and S_w is 66% against Sand -6A in the interval XX16.0 – XX20.0 m

(Object –I). On production testing of this interval no influx was found. Similarly S_w against Sand -6B was computed as 77.5 % considering R_t equals 5.2 ohm-m and Φ_e equals 0.31p.u in the interval XX11.5 – XX13.0 m

(Object – II) . On activation during production testing the interval produced little water having Salinity 3.49 g/litre. Object –III was identified in Sand -11, in the interval XX56.0 – XX60.0 m. Standard formation evaluation yields R_t is 5.2 ohm-m , $\hat{0}_e$ is 0.22 p.u and S_w is 57 % . During production testing the Object has flowed water of Salinity 2.91 g/litre and does not follow with the traditional approach of Log evaluation.

NMR log data is then incorporated to analyse the above production performance of each Objects. It shows Sand -6A (Object – I) is comprising of micro pores and free fluid porosity is almost absent in this interval (Refer Fig 5).

Though S_w value is optimistic and marginal but computation is affected due to high density porosity (Φ_d) reading due to bad hole condition. NMR log shows high volume of bound water present in this interval and explains the production testing result. Object –II against Sand – 6B is having few concentration of larger pores as per NMR log response as well as high water saturation against it and matches the testing result.

NMR log response against Sand -11 (Object –III) shows presence of meso to macro pores (Refer Fig: 6). NMR free fluid porosity is 15 % and permeability is around 100 md indicating favorable reservoir quality of this Sand unit.

Fluid typing was attempted here, because new generation CMR PLUS* tool was run in this well. This tool is capable for fluid characterization in stationary mode. Magnetic resonance fluid (MRF) characterization was attempted at the depth XX57.0 m against Sand -11 (Object –III). Though computed S_w is optimistic against this sand, fluid typing from MRF confirms the presence of single phase i.e. water and no oil component is present (Refer Fig: 7).

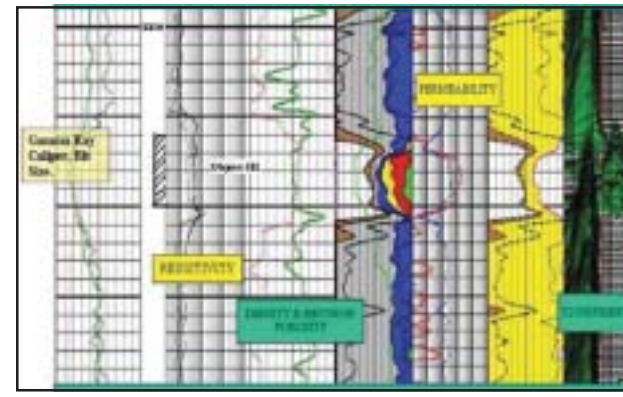


Fig.6: Resistivity – NMR log composite against Object-III (Sand -11) of Well No. G-II

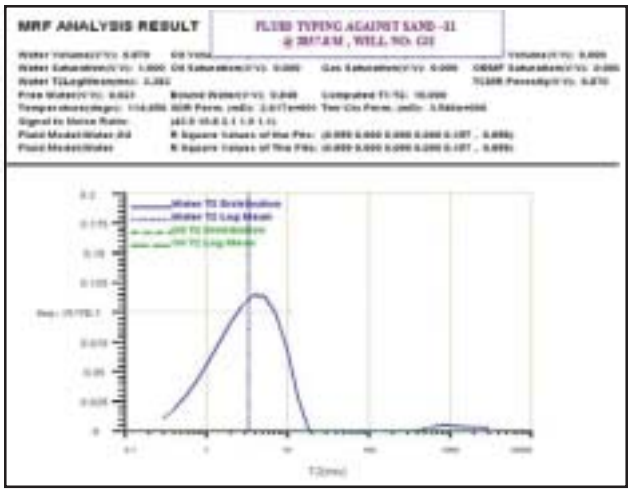


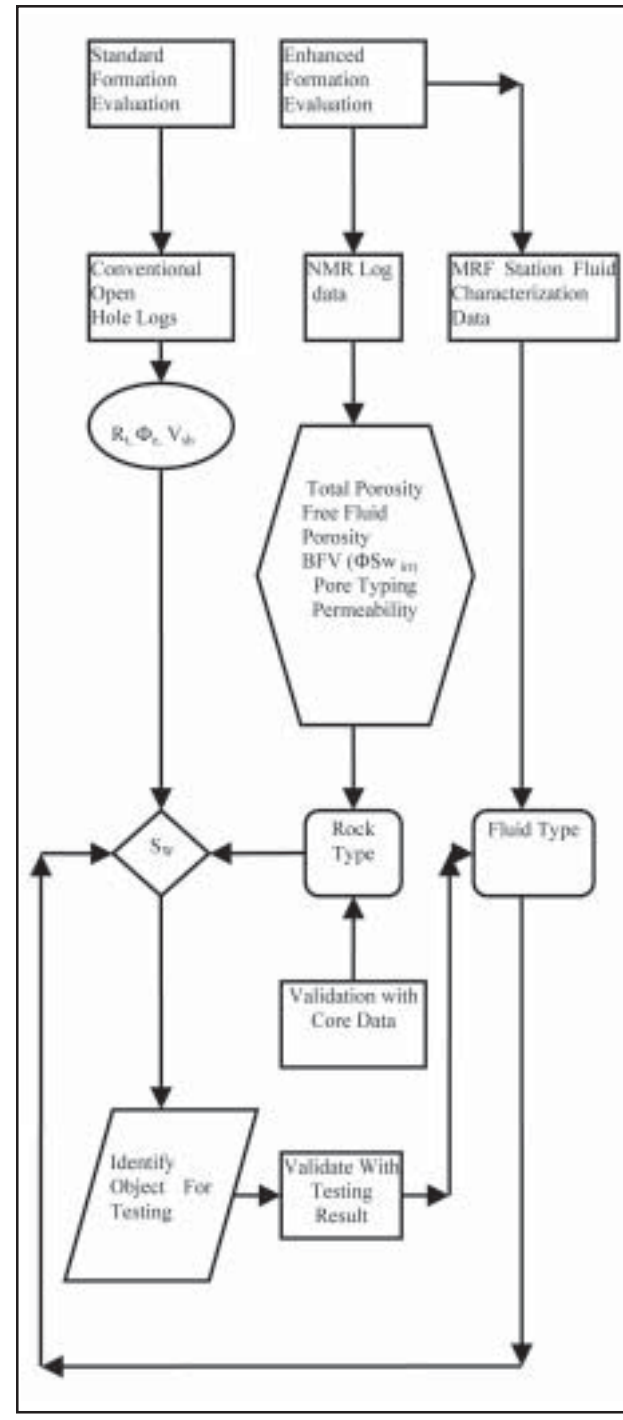
Fig. 7: NMR Fluid Characterization (MRF) analysis against Object-III (Sand- 11) of Well No: G-II.

Later, production testing result confirms the above observation. Presently this well is abandoned.

Conclusions

The study has revealed that reservoir properties e.g. rock properties and fluid properties can be evaluated in a better manner by integrating NMR data with conventional open hole log data. Two examples presented in this article above clearly depicts that producibility of the sand unit can be explained more correctly, if NMR log data is combined with standard formation evaluation, where stand alone traditional formation evaluation technique found to be inconclusive. However, this study was carried out with a limited data set.

Hence, it will be unwise to draw any broad based conclusion. New generation wireline NMR tool e.g. MR – eXPERT * can do fluid characterization in continuous mode unlike station mode acquisition in CMR- PLUS. More availability of such data and further work in this direction may help to explain the reservoir behavior in a better way. So that suitable exploitation and reservoir management scheme can be planned and implemented. In turn, this will help to improve the recovery efficiency (Producibility) from the reservoir and more and more hydrocarbon can be extracted from mother earth making our tomorrow brighter.



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