Petrophysical Analysis of Unconventional Reservoirs Using Conventional Logs

Naresh Kumar, Ashutosh K Singh, Vidya Mundayat and Lalaji Yadav
E&P Business, Reliance Industries Limited, RCP, Ghansoli, Navi Mumbai, 400701, India
naresh.b.kumar@ril.com

Abstract

Unconventional reservoirs are becoming increasingly important day by day around the globe due to rapid depletion of conventional reservoirs. Unconventional reservoirs are those reservoirs which have low permeability and effective porosity and are difficult to produce by conventional methods.

Identification of these reservoirs is difficult as they show more affinity to shale than sandstone or limestone on log character. Sometimes it is misinterpreted as shale. Due to this character, quantification of porosity and water saturation in these reservoirs is also challenging. Generally special logs like NMR and core measurements are not available to properly evaluate such reservoirs. Derivation of porosity is very difficult in absence of core measured grain density, particularly when lithology is predominantly shale/silt with varying grain density.

An integrated petrophysical evaluation methodology has been developed using conventional logs to identify unconventional reservoirs and evaluation of porosity and water saturation. The methodology uses SP log in combination with other conventional logs to identify such reservoirs. Formation water resistivity is calculated using SP log. Total porosity is derived using resistivity log in known water zone. This porosity has been used for estimation of zone wise average grain density followed by porosity estimation from density log. Finally, water saturation computation is performed by using Archie equation. Derivation of porosity and water saturation using resistivity has been performed without any correction of clay conductivity, which is suppressed due to very high salinity of formation water in the cases considered.

The methodology has been used for petrophysical evaluation in number of wells in Cambay basin in which only conventional logs were available and grain density measurements were not available. The results obtained are validated with NMR log and porosity measurements on SWC samples available in a well.

Introduction

The last two decades have witnessed a growing interest in low permeability reservoirs named unconventional reservoirs due to rapid depletion of conventional reservoirs. The definition of unconventional reservoir system given by Sondergeld (2010) is “hydrocarbon reservoir with complex geological and petrophysical systems as well as heterogeneities”.

Unconventional reservoirs are characterized with low effective porosity and permeability, small drainage radius and low productivity; require significant well stimulation like hydraulic fracturing or the use of horizontal or multi-lateral wells to produce at economic rates. Typical lithology of unconventional reservoirs are shale, sandstone/siltstone and sometimes carbonate with permeability less than 0.1 mD. The complicity of these reservoirs is attributed to:

a) Low effective porosity and low permeability.
b) The presence of clay minerals like illite, kaolinite and micas in pores.
c) The heterogeneity of the reservoir in vertical and lateral directions.

Identification and evaluation of unconventional reservoirs is challenging. On conventional logs, these reservoirs are characterized by low resistivity, low resistivity contrast between reservoir and non-reservoir rocks, relatively higher gamma ray activity and shale like separation on density-neutron logs. Sometimes it is misinterpreted as shale by log analysts. Generally special logs like NMR and core measurements are not available to properly evaluate such reservoirs. Use of NMR in individual basis or in combination with conventional open hole logs leads to better determination of petrophysical properties of unconventional reservoirs.

Nuclear magnetic resonance (NMR) logs differ from conventional neutron and density porosity logs, NMR signal amplitude provides detailed porosity free from lithology effects and radioactive sources and relaxation times give other petrophysical parameters such as permeability, capillary pressure, the distribution of pore sizes and hydrocarbon identification.

This paper deals with a new petrophysical methodology to evaluate the unconventional reservoirs and estimation of average petrophysical parameters using conventional logs. The methodology has been applied to a number of wells in Cambay Basin. Examples of two wells have been presented in this paper. The methodology has been validated with NMR log, SWC results and formation testing results in second example.

Study Area

The area under study is in Cambay Tarapur tectonic block of Cambay basin (Figure l). The Cambay Basin is situated on the northwestern part of the Indian shield, which is a rift-system extending for about 425 km. in a NNW-SSE direction and progressively widens southward up to 100 km.

The basin is mainly concealed beneath the alluvial plains of the Gujarat and the Gulf of Cambay. The Basin is bordered by the Middle Proterozoic Aravalli-Delhi fold belt in the east and the Saurashtra arch in the west. The Basin is composed of up to 7-8 km thick Cenozoic stratigraphic succession, which records at least 66 m.y. of basin formation and subsidence history. The Deccan basalts (Late Cretaceous to Early Paleocene) occurring in most parts of the Basin floor constitute the technical basement of the Cenozoic sediments.

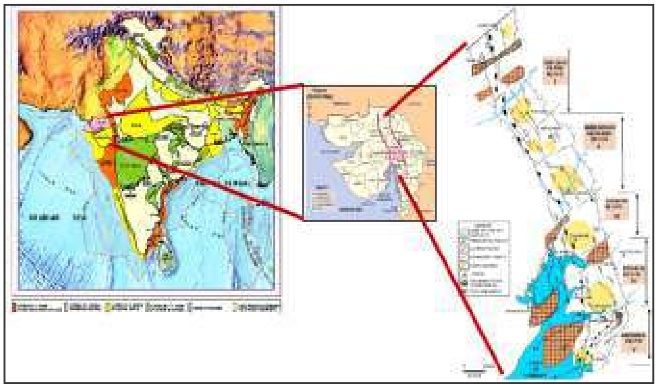

Fig. 1: Map of Study Area

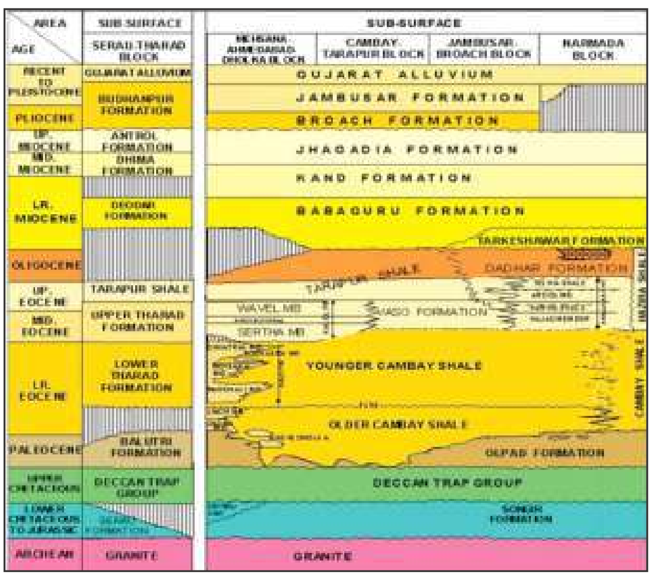

Fig. 2: Stratigraphy of the area

The Deccan Trap (Late Cretaceous / Earliest Paleocene) forms the basement. It mainly consists of basalt. The Deccan Trap is overlain by Olpad Formation of Paleocene age, composed of conglomerates, sand, sandstone, silt, siltstone and clay, derived from the Deccan trap basalts. It is overlain unconformably by organic-rich black shale widely known as Cambay Shale of Late Paleocene to Early Eocene age. In the northern part of Cambay Basin, in which the present study area is located, Cambay Shale is further subdivided into Older Cambay Shale (OCS) and Younger Cambay Shale (YCS). The Kadi Formation is present only in the Ahemadabad - Mehsana and Sanchor - Patan-Tharad tectonic blocks. There is a pronounced angular unconformity between the Kadi Formation and the overlying (post-rift) Kalol Formation. The Kalol Formation (Middle Eocene) is composed of intercalation of sandstones, shale and coal.

The Kalol Formation is overlain by thick gray-Shale of middle Eocene to Oligocene age known as Tarapur Shale, considered to be the regional cap for Kalol Formation. Tarapur Shale is then overlain by the Oligocene Babaguru Formation predominantly composed of sandstones, with lesser amounts of mudstone, conglomerate and siltstone, followed by Kand Formation. The Kand Formation is composed predominantly of Shales, with thin intervals of medium to coarse grained sandstones. Kand is overlain by the Jhagadia Formation. The Gujarat alluvium of Holocene age forms a cover for these sediments in the Cambay Basin. Stratigraphy map of Cambay Basin is shown in Figure 2.

Petrophysical Processing Methodology

Unconventional reservoirs of area under study mainly consist of shale and silty sand facies as well as thin sand / shale laminations, which have poor effective porosity and permeability. Often the properties of these reservoirs are underestimated because of vertical resolution of conventional tools and complex lithology.

Hydrocarbon presence is major concern in most of the unconventional reservoirs. To identify presence of hydrocarbons and to evaluate these unconventional reservoirs, a new methodology has been developed to evaluate the unconventional reservoirs of Cambay basin using SP, density and resistivity logs. The methodology has been validated with NMR log recorded subsequently.
The methodology is outlined below:

- The Resistivity of formation water (Rw) used for the analysis is calculated from SP log.
- Grain density is derived by back calculating from Rw derived from SP log and resitivity log in water bearing low resistivity shale.
- Total Porosity is calculated from density log using the zone wise grain density derived in previous step.
- Archie equation is used for water saturation computation with m=n=2. Derivation of porosity and water saturation using resistivity has been performed without any correction of clay conductivity, which is suppressed due to very high salinity of formation water in the cases considered.

The porosity and water saturation thus derived are in total domain.

Resistivity of Water

Resistivity of water is calculated from SP log. The unconventional reservoirs under study area are characterized by SP development w.r.t. SP shale base line. In a particular formation SSP is determined for formation water resistivity (Rw) calculation. The SSP is positive or negative based on the resistivity of mud and resistivity of formation water.

There are five steps for calculating Rw from the SP log. The list below summarizes these steps:

- Estimate formation temperature.
- Convert Rmf to formation temperature.
- Convert Rmf to Rmfeq.
- Read SP response against interesting zone with respect to shale base line (SSP) and estimate Rwe.
- Convert Rwe to Rw at formation temperature.

Grain Density

Unconventional reservoirs are mostly complex in nature from lithology point of view. In the absence of grain density and X-Ray Diffraction (XRD) measurements, it is difficult to evaluate the formation porosity. In this work, grain density is calculated using SP log.

Resistivity of water from SP log, as calculated in earlier step, is used against the low resistivity shale (water bearing) section and then porosity is back calculated from formula given below:

$$Rw = (\varphi^2)\ RT$$

From this porosity, the average grain density in particular zone is back calculated from density log from following formula:

$$r\ ma = \frac{(RHOB - f)}{(1 - f)}$$

Where:

- RHOB: Density Log
- ρma: Matrix Density
- φ: Porosity

Grain density thus calculated is used for porosity computation in entire zone.

NMR measurements now have the ability to provide lithology-independent total porosity measurement. Total porosity using NMR T_2 decay amplitudes depends on the hydrogen content of the formation. Total NMR porosity is almost equivalent to the density porosity in water filled formation.

Grain density is also calculated using NMR total porosity for entire zone and the formula is given below.

$$r\ ma = \frac{(RHOB - TCMR)}{(1 - TCMR)}$$

Where:

- TCMR: Total Porosity from NMR log

Grain density from NMR log is calculated for entire zone of interest and average value of zone is taken as grain density for estimation of porosity. This grain density has been used for validation of SP derived grain density.

Porosity and Water Saturation

Total porosity from Density log is computed from following equation:

$$\phi = \frac{(\rho ma - Rhob)}{(\rho ma - \rho fl)}$$

Where:

- Rhob: Density Log
- ρma: Grain Density as derived in previous step
- ρfl: Fluid Density
- φ: Porosity

Archie (1942) equation with m=n=2 has been used for water saturation computation:

$$(S_W)^n = \frac{aR_w}{(\phi)^m R_t}$$

Where:

- Sw: Water Saturation
- Rw: Resistivity of Water
- Rt: Formation Resistivity
- φ : Total porosity as derived in previous step
- a: Tortuosity factor
- m: Cementation Exponent
- n: Saturation Exponent

Water saturation from the NMR log is also calculated using following equation:

$$SWT = \frac{(BFV)}{(TCMR)}$$

Where:

SWT: Water saturation in total domain
BFV: Bound Fluid Volume
TCMR: Total NMR Porosity

The NMR derived water saturation has been used to validate the water saturation derived from proposed methodology.

Results and Discussion

Two wells from area under study are presented here. Well A was drilled under Phase-I exploration campaign in 2009. In this well only conventional logs were recorded. Well B was drilled in Phase-II exploration campaign in 2016. In well B special logs like NMR were also recorded. In well B, porosity measurements on SWC samples are also available.

Well A:

In well A, unconventional reservoirs within Kalol formation have been identified from SP development. Formation water resistivity from SP log was estimated as 0.05

ohm-m at formation temperature. From this Rw grain density is estimated as 2.78 gm/cc in the zone of interest.

Using this Rw and grain density, porosity and water saturations are computed and results are shown in Figure 3. The interval XX07-XX60 m is interpreted as hydrocarbon bearing with average total porosity and water saturation of 25% and 45% respectively.

Based on the analysis, the hydrocarbon bearing interval was recommended for testing.

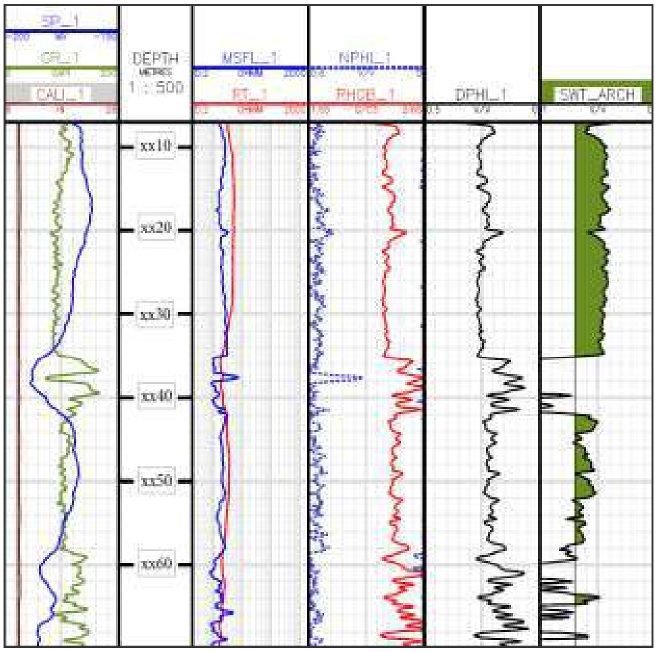

Fig. 3: Composite log plot of well A

Well B:

In well B, the zone of interest is in Olpad formation. Formation water resistivity from SP log is estimated as 0.08 ohm-m at formation temperature. From this Rw grain density is estimated as 2.68 gm/cc. Average grain density is also computed from NMR log as 2.68 gm/cc (Figure 4). The gain density calculated from SP log is matching with the average grain density computed from NMR log.

Porosity is computed from density log from grain density as derived above. A log motif of density derived total porosity (DPHI) and NMR derived total porosity (TCMR) is shown in Figure 5. The porosity estimated on SWC samples is also presented in the Figure. The porosity derived from density log is showing very good match with NMR derived porosity and SWC measured porosity.

Archie's equation is used for estimation of water saturation. The water saturation derived from proposed methodology and NMR log are presented in Figure 5.

Water saturation thus derived and NMR are showing good match thus validating the methodology. A MDT-Saturn sample at YY25.5 m confirmed presence of gas.

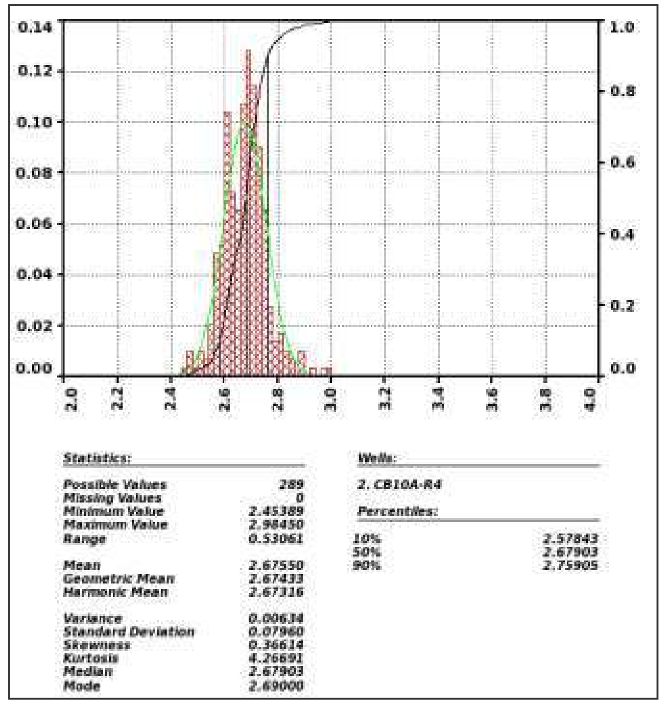

Fig. 4: Histogram of Grain density from NMR log in well B

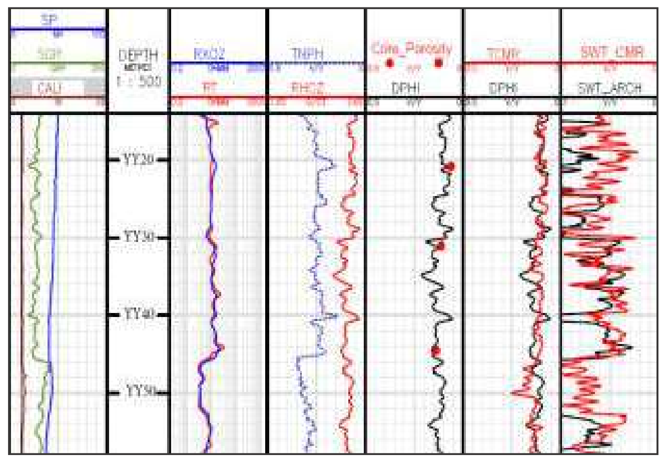

Fig. 5: Log motif of study area showing porosity and water saturation in well B

Limitation

This methodology provides porosity and water saturations in total domain. As hydrocarbon in place calculations require product of porosity and hydrocarbon saturations and product of porosity and hydrocarbon saturation remains constant in total and effective domain, it does not matter for in place calculations. However this methodology does not indicate whether hydrocarbon is producible or not. NMR free fluid porosity is a good indicator of hydrocarbon producibility. It has been assumed that presence of hydrocarbons is not affecting SP development in unconventional reservoirs in area under study.

Conclusions

The following conclusions can be drawn from the study:

- The unconventional reservoirs are becoming important day by day.

- Petrophysical evaluation of unconventional reservoirs is challenging due to their complex nature. A methodology has been proposed for evaluation of such reservoirs.
- SP log is used to calculate the formation water resistivity.
- Grain density has been calculated from combination of Rw & density log. The grain density thus derived is validated with grain density derived from NMR log.
- Total porosity from proposed methodology is showing very good match with NMR total porosity and porosity measurements on SWC samples.
- Water saturation from proposed methodology is showing good match with NMR and water saturation. Formation tester sample also corroborate the evaluation.

Acknowledgments

Authors are thankful to the management of Reliance Industries Limited for granting permission to present and publish the paper. The authors are also grateful to Shri Neeraj Sinha, Head Exploration, for encouragement during the work.

Reference

Archie, G. E., 1942, The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics, Trans. AIME Vol. 146, 1942.

Biswas, S.K., Bhasin, A.L., and Ram, Jokhan, 1993, Sedimentary basin map of India, A tectonic classification, Explanatory notes: Dehradun, India, KDIMPEOil and Natural Gas Commission, p. 22.

David Allen, et. al., 2000, Trends in NMR logging. Oilfield Review.

Dewan, J. T., 1983, Essentials of modern open-hole log interpretation: Tulsa, OK, Penn Well Books

Harris Cander., 2012, What Are Unconventional Resources? A Simple Definition Using Viscosity and Permeability* Search and Discovery Article #80217.

Khlaifat A. and Qutob H., Unconventional Tight Gas Reservoirs Future Energy Source. Materials in Jordan, Amman, Jordan, 10-12 April, 2010.

Naik, G.C., 2010, August 23rd- “Tight Gas Reservoirs An Unconventional Natural Energy Source for the Future”.

Petrophysical evaluation of Tight Reservoirs of Cambay Basin, Unpublished Report of Reliance Industries Limited, 2015.

Sondergeld, C. H. et al, 2010, Petrophysical Considerations in Evaluating and Producing Shale Gas Resources, Paper SPE 131768, SPE Unconventional Gas Conference, Pittsburg, Pennsylvania.