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An Integrated Petrophysical Study for deep water turbidite reservoir to improve Hydrocarbon Saturation

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Summary

Characterization of thin beds in deep water turbidities is always a challenging job. Often we are encountered with thin lamination of sand and shale in addition to thick clean sands. The thick sand are resolved properly but over thin beds log records average properties of sand and shale. Saturation estimated from the conventional resistivity measurements are dominated by high conductive thin shale and fine grained sands which obscure the presence of more resistive hydrocarbon bearing sands. Direct interpretation of the log reading therefore results in a significant underestimation of hydrocarbon saturation.

In general reservoir engineers prefer to estimate hydrocarbon saturation using capillary method. The method works well if constrained with core data, however in deepwater exploration due to very high rig cost coring is not preferred option. Therefore, petrophysicist were looking for an alternate option. With the wider acceptability of triaxial induction log and its calibration with core results, it can be used as a constraining mean for the saturation height function. This paper is a case study of a field-scale integrated thin-bedded, shaly sand petrophysical evaluation and hydrocarbon reserve estimation in the field, east coast of India. All the wells drilled in this field intersected shaly sand, thin laminated shale-silt –sand sequence, blocky sand. The resistivity anisotropy data is available for four wells out of the total twelve well drilled.

This paper reviews two methodologies, one using saturation estimation by Leveret "J" function and second method by field derived resistivity anisotropy data. The final results of the anisotropy and "J" function derived hydrocarbon saturation are compared and are found to have very good match. Afterwards the"J"function was used for final saturation estimation over rest of the well for reserve estimation purpose.

Introduction

The major problem in studying thin-layered and shaly sand reservoir is identification of net pay and reliable assessment of hydrocarbon saturation. The main difficulty arises from the low vertical resolution of standard resistivity tools. More specifically in laminated formations, thin beds of fine grained sand, silt and clay distributed within hydrocarbon bearing formation significantly reduce the apparent resistivity. The problem become more acute in deep water formation evaluations since exploration and development costs are much higher and therefore, there are needs to find out a way to properly characterize the reservoir by different tool and technique. With the discovery of many Gas/Oil fields in the deep waters, it is important to estimate the prospective resource available with in the different blocks. Worldwide 30-40% of the in place resources are confined within thin beds; therefore it is important to find their true potential with minimum uncertainty. There are various techniques available in the industries for the net pay estimation like, counting laminations using the image logs, lam count study on cores, etc .But the real challenge lies in the hydrocarbon saturation estimation. Some experts like to assign the same hydrocarbon saturation and porosities to thin beds as that of the thick beds. Some prefer to classify the facies based on the resistivity micro-image logs and then carry out de-convolution to derive the properties of the beds using Inverse modeling technique. Both have some advantages/ disadvantages.

The thin-bed petrophysical analysis methodology used ie 'Resistivity Anisotropy', instead of identifying and

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revealing individual thin –beds in a unit of rock, it studies the resistivity anisotropy caused by the presence of thin sand-shale sequences, first the horizontal and vertical resistivities are determined and then used in the computation of R-sand and R-shale. Next a thin–bed petrophysical evaluation is performed using a bi-modal petrophysical property distribution. In a unit of rock, the model accounts for hydrocarbon held in a clean sand, as well as hydrocarbon possibly contained in shale-sand-silt laminae. Another methodology used is saturation height function. Saturation height functions are mathematical expressions that are used to evaluate water saturation Sw, from height,H in true vertical space. There are various practical techniques for correlating capillary pressure curves according to rock type for heterogeneous formation and generating field wide saturation- height functions that relates capillary pressure curves to porosity, permeability or rock type in general.

The following section describes objective, theory, workflow and methodology used; for'Resistivity Anisotropy' and' Saturation Height function'. The final results are presented and compared.

Methodology

Hydrocarbon saturation estimation across the thick clean sand have minimum amount of uncertainty. All methods compute the similar properties in thick sands. However problem comes in case of thin sand shale laminations. Resistivity measured by the conventional laterolog or induction device is reduced by the high conductive shale laminae. Moreover, fine grained layers frequently have high irreducible water saturation and therefore the reservoir can produce oil or gas with zero water cut. In petrophysical sense beds thinner than vertical resolution of logging device is known as thin beds.

To over come the problem of hydrocarbon saturation under estimation various techniques were tried and it was found that if resistivity anisotropy and saturation height function were constrained properly, the uncertainty can be reduced to minimum over the field. In the absence of anisotropy data it was generated using empirical relationship established from the wells having it. The detailed workflow of the two techniques is described below in details.

1. Field derived Resistivity anisotropy method

2. Thin bed analysis using Saturation height function.

Resistivity Anisotropy Method

In a clean and electrical homogenous, thick formation, the standard induction log response results in Rt and a resistivity based saturation analysis is straightforward. However, in thin-bedded sand-shale sequence that is below the vertical resolution of the instrument, additional information such as shale volume, its distribution and resistivity is needed for an accurate saturation analysis. Traditional approaches of thin-bed reservoir evaluation have concentrated on determining formation parameters by increasing the vertical resolution of the instruments. At the same time, electrical resistivity measurements must investigate deep in to the formation beyond drilling fluid invasion. However decreasing the transmitter-receiver spacing to increase vertical resolution results in decreased depth of investigation. Thus very high- resolution electric logs are mostly dominated by near well bore invasion results.

Resistivity anisotropy tool incorporates additional XX and YY transmitter-receiver coil arrays that are mutually orthogonal to the ZZ array along the tool axis and to one another. In vertical well with horizontal beds, the additional XX and YY arrays induce currents in the formation that flow across the laminae. This transmitter-receiver configuration provides all necessary data to compute horizontal (Rh) and vertical resistivity (Rv).additionally multifrequency focusing techniques are used to minimize borehole and invaded zone conductivity effects, Kregshauser, et al , 2000.

n a vertical well with horizontal bedding, the formation response acts as a resistor in parallel circuit and the horizontal measurement, Rh is dominated by low resistivity shale, Rshh.

$$\frac{1}{Rh} = \frac{(1-Vlam)}{Rsd} + \frac{Vlam}{Rshh}$$

In contrast, the vertical response acts as resistors-in – series circuit and the vertical resistivity measurement Rv is dominated by the high resistivity hydrocarbon bearing sand, Rsd.

$$Rv = (1\text{-}Vlam) * Rsd + Rshv * Vlam$$

Anisotropy derived horizontal and vertical resistivities ,Rh and Rv, together with user defined horizontal and vertical shale resistivities, Rshh and Rshv,are used to calculate the laminar sand fraction resistivity, Rsd such that

$$Rsd = 0.5 * ((Rsub + Rshv) + (Rsd - Rshv) * (1+\Delta R)1/2)$$

Where

$$Rsub = Rh * \frac{(Rv - Rshv)}{(Rh - Rshh)}$$

$$\Delta R = 4 * Risd * \frac{(Rshv - Rshh)}{(Risd - Rshv)}$$

Laminar shale volume, Vlam is calculated using Rsd from equation given below

$$Vlam = \frac{(Rsd - Rv)}{(Rsd - Rshv)}$$

These results are used to determine sand fraction water saturation from the Waxman-Smits, 1968, equation or Archie's1942, relationship.

Workflow

- Calculate reservoir true resistivity (Rsand) resistivity (Rshale) from Rv and Rh.
- A relationship between Rv and Rh for sand and shale zones (fig 1 & 2) has beenestablished for the wells having anisotropy data using regression analysis. The predicted Rv is then compared with measured Rv (fig 3) and showing good match with measured data which gives the more confidence about the resistivity anisotropy transform. The resistivity transform has of following form:

$$Rv\_Shale = 10^{(0.412698 + 0.843408 * \log10(Rh))}$$

$$Rv\_Sand = 10^{(0.20713 + 1.03831 * \log10(Rh))}$$

The above transform are used to predict the Rv curve for wells where measured data were not available.

- Estimation of laminated/dispersed shale fraction and sand porosity using ThomasStieber method
- Calculation of water saturation (Sw) using reservoir true resistivity (Rsand) and Porosity as input.

Saturation Height Function

Reservoir water saturation decreases with increasing height above the FWL (free water level), where capillary pressure is zero. Minimum water saturation (Swirr) is reached at a great height above the FWL and this water saturation is immobile. Variation in the capillary radius is controlled by the pore geometry, which is a function of rock properties such as permeability and porosity. Hence, pore size distribution has a major influence on the magnitude of the irreducible water saturation and the extent and height of the transition zone. The hydrocarbon water contact (HWC) will vary with depth as a function of reservoir quality ie higher the permeability, the smaller the separation between the OWC and the FWL.

Saturation height functions are mathematical expressions that are used to evaluate water saturation Sw, from height, H in true vertical space. There are various practical techniques for correlating capillary pressure curves according to rock type for heterogeneous formation and generating field wide saturation- height functions that relates capillary pressure curves to porosity, permeability or rock type in general. Saturation height function has taken many forms through different decades by numerous authors.

Leverett(1941) introduced a dimensionless "J" function equation (1) to convert all capillary data to with similar pore geometry to a universal curve. The Cos (θ) term was added later to include wettabilty effect. The $(k/Ø)^{0.5}$ terms is the pore geometry factor and is used to normalize petrophysical properties such as capillary pressure, relative permeability and residual saturations. The proposed approach in this paper is based on equation (1).The term Pc can be derived from equation (3) or (4)

$$J(Sw) = \frac{Pc}{\sigma \cos(\theta)} * (K/Ø)^{1/2} \quad \text{......................(1)}$$

$$J = a\,(Sw)^{b} \quad \text{..................................(2)}$$

$$Pc = (\rho 1 - \rho 2)\, gh \quad \text{..................................(3)}$$

Or

$$Pc = (FWL - TVD) * 0.4338 * \Delta SG \quad \text{....................(4)}$$

Where g is acceleration due to gravity and ρ1 and ρ2 are densities of wetting and non-wetting phases.

Workflow

- Calculate capillary pressure using equation (3) or (4).
- Calculate porosity and permeability from conventional techniques.
- Estimate saturation using the equation (1)&(2)

Comparison

Saturation height based Sw is more flat over the interval. It is more controlled by the porosity and permeability of the formation rather than the distance from the adjacent bed. The difference between the different techniques is more visible over the shaly sand interval (fig.4), where conventional and anisotropy is showing higher saturation. The interval have more dispersed shale and are not having the anisotropy, therefore resistivity anisotropy method will also not correct the effect of dispersed shale. The various techniques of shaly sand analysis will help in combination with change in m & n parameter. The saturation height function, in this case is giving the better saturation, which when tested have flown gases without any water production. Thus it further validates the result of capillary height function.

Therefore it is good to calculate the petrophysical properties using more than one technique and then constrain them with one another.

Discussion of Results

Water saturation was estimated using both anisotropy and saturation height function. Porosity was estimated using the Thomas-steiber method and the same has been used in both the technique. Data of 4 wells has been presented in the fig(5,6,7&8)Track 1 shows the GR, in Track 2 total and effective porosities are plotted .Track 3 shows all the 3 water saturation ie,(1) using the conventional Rt(Swe-Rt),(2)using resistivity anisotropy(Swe-RvRh) and (3) using capillary pressure(Swcap).

The comparison shows that saturation estimated using the conventional Rt is high over laminated section whereas saturation height and anisotropy have the similar saturation. Bed boundary effect is more pronounced in the resistivity based methods (both conventional and anisotropy due to averaging over the bed boundary), where as not in saturation height method.

Conclusion

1. Estimation of hydrocarbon saturation using the conventional method leads to underestimation.

2. Resistivity anisotropy method gives a good approximation for realistic Sw over laminated section. However still some bed boundary effects are seen.

3. Since Resistivity anisotropy is relatively very new technique, therefore data in the old wells is not available.

4. Empirical relationship can be used in old wells to generate the vertical resistivity and the same can be used for saturation estimation.

5. Saturation height function based saturation should also be estimated as the field based approach.

6. Both the saturation should be constrained with each other over clean and laminated section to have a better control.

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Nomenclature

Vlam = Laminar shale volume

Risd = isotropic sand resistivity

K = Permeability

Ø =Porosity

Pc = Capillary Pressure

J (Sw) =Leverett's J –function, dimensionless

σ = Interfacial tension, dyn/cm

θ =Contact angle between wetting and non-wetting phases

ΔSG = Specific gravity difference between wetting and non-wetting phases.

TVD =True vertical depth.

'a' and 'b''= constants

Figures

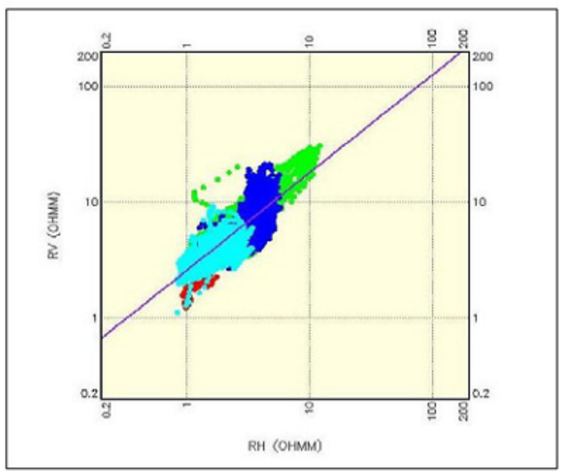

Fig: 1 Plot showing Rv and Rh relationship in shale

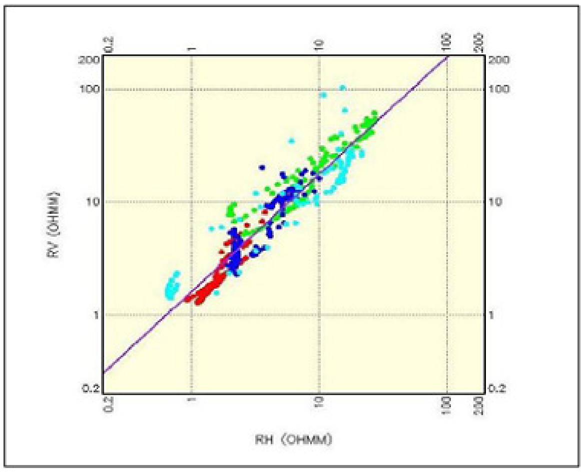

Fig: 2 Plot showing Rv and Rh relationship in sand

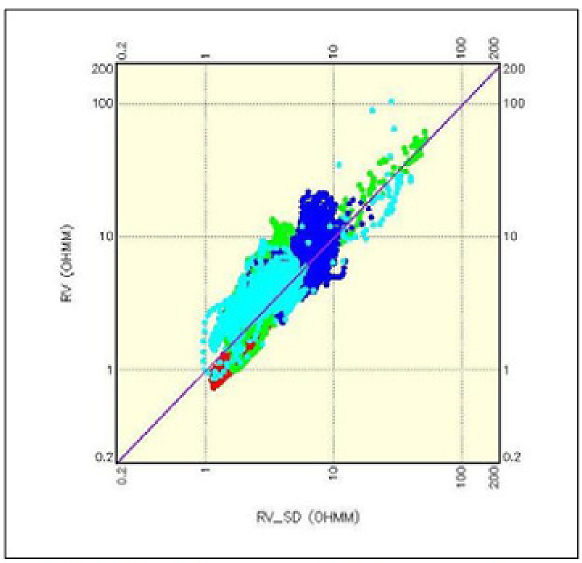

Fig: 3 Plot of Rv computed Vs Rv measured

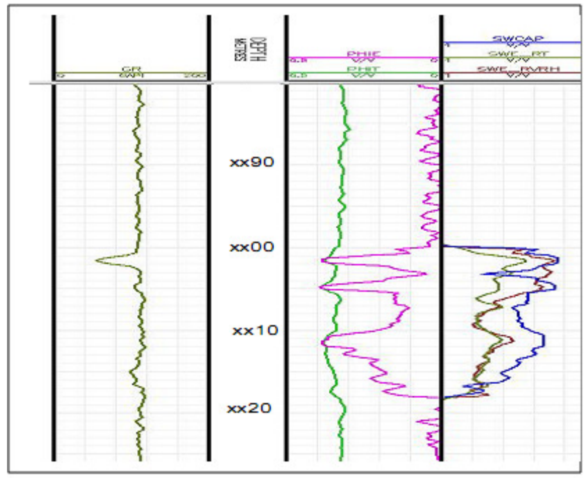

Fig: 4 Plot showing shaly sand interval

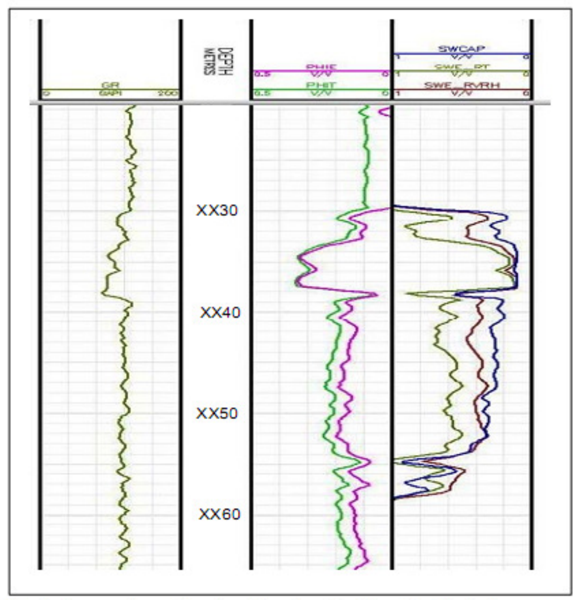

Fig: 5 Comparison plot showing Swe-Rt, Swe-RvRh & Swcap

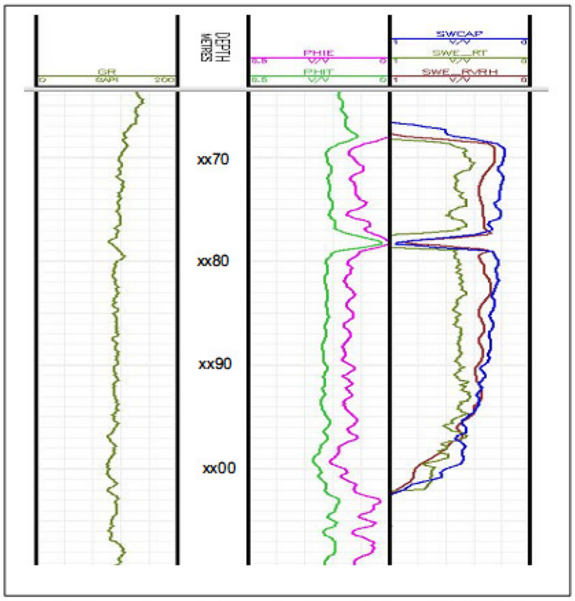

Fig: 6 Comparison plot showing Swe-Rt, Swe-RvRh & Swcap

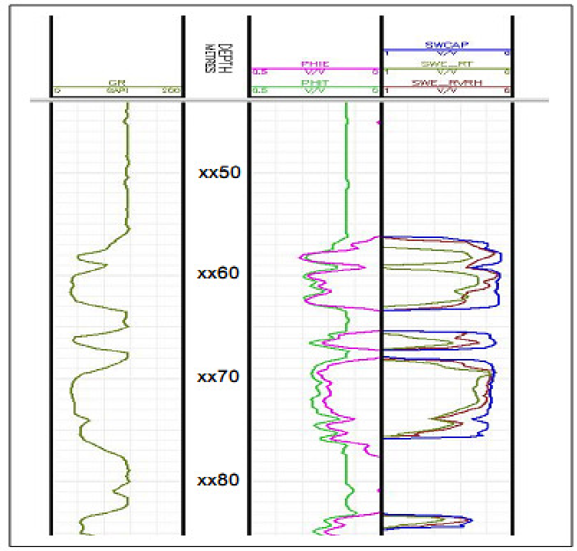

Fig: 8 Comparison plot showing Swe-Rt, Swe-RvRh & Swcap

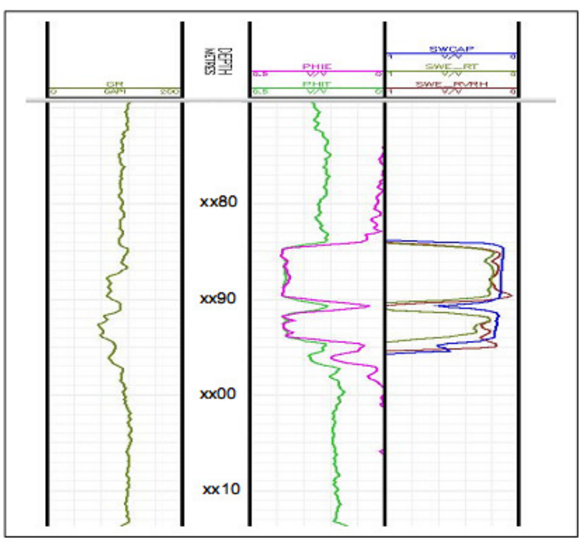

Fig: 7 Comparison plot showing Swe-Rt, Swe-RvRh & Swcap