Evaluation of Low Resistivity Laminated Shaly Sand Reservoirs

Dr S S Prasad, C S Sajith & S S Bakshi
Sub Surface Team, Mehsana Asset, ONGC, Palavasna, Mehsana, Gujarat
E-mail : shivshankarp@gmail.com

Summary

About 30% of the world's estimated hydrocarbon reserves are contained in laminated, low-resistivity, low-contrast; shaly sand formations. More often than not, these are either considered uneconomical or do not even draw the attention of the petrophysicist. In laminated reservoirs, the conventional resistivity tools sense the laminated formation as an effective medium with a low horizontal resistivity parallel to the laminae and a higher vertical resistivity perpendicular to the laminae. In vertical wells, only the horizontal resistivity is measured, while in directional wells the tool becomes increasingly sensitive to the vertical resistivity as the angle of inclination increases. As most of the wells logged in Cambay Basin have only conventional resistivity logs, chance of missing low resistivity pays due to anisotropy and bed/well inclination is quite high. The present study is directed towards extracting realistic resistivities of the pay zones with the knowledge of shaliness, shale resistivity and inclination angle of the well/bed.

This study assumes that in laminated pays, shale - sand sequence are parallel to each other. The basic postulate, which has its roots in geologically conceived sedimentation pattern, states that the shales within a laminated pay has the same property as that of a thick shale in immediate contact of the sequence. The conventional measurement of resistivity in the case of a vertical well is the equivalent resistivity of resistances in parallel and for a horizontal well it is that of the resistances arranged in series. Starting with Archie's equation in generalized form a formula has been derived for *Sw*, which is an improvement over Roberto Aguilera (1990). A formula for the case where the axis of measurement of the tool is not parallel to the formation layer has been developed. Case studies are presented which show that the improved formulas yield better results in laminated reservoirs.

Introduction

Laminar clays are distributed in a reservoir as relatively thin layers of allogenic clay or shale that has been deposited between clean layers of sand. The overall laminations reflect multiple cycles of deposition under a dual flow regime, characterized by fluctuations in energy levels. These shale laminations of such shaly sand reservoirs do not affect the resistivity, porosity or permeability of the surrounding sand streaks themselves, and a shale fraction of up to 60% can therefore be reconciled in the reservoir.

If such layers are encountered within bed thickness of less than 5 feet, most of the conventional resistivity tools (induction tools) lack the vertical resolution to differentiate between individual thin beds of sand and shale. The advanced versions of induction tools with vertical resolutions of the order of one foot have also been found wanting since, in practice, examples of individual lamina with thickness of 6 inches or even less are not uncommon. In this context it is emphasized that the angle between the axis of conventional resistivity tool and the bed plays a very important role on the response of the tool, which is also elucidated by Luling, et al (1994).

Previous work

Shray and Borbas (2001) advanced a procedure to assess water saturation in laminated sand formations based on the use of nuclear magnetic resonance (NMR) measurements and estimates of resistivity anisotropy. Accurate calculation of fluid saturation is possible only with a methodology that combines resistivity anisotropy and high-resolution borehole measurements such as NMR and borehole imaging. Forsyth et al. (1993) proposed a parallel resistivity model to assess water saturation in a laminated clastic hydrocarbon field located off the coast of Brunei. Their interpretation method combines rock-core data (or borehole image logs), production data, and resistivity measurements acquired with conventional induction tools. Even though their interpretation increased the value of in place hydrocarbon reserves by 10%, Forsyth's method is relatively less successful for thinner lamina vis à vis the vertical resolution of the tool. Roberto Aguilera (1990) discussed method of computing *Sw* using Picket Plots wherein the parallel resistivity model was used. However Kennedy and Herrick (2004) suggest that the saturation and porosity exponents depend upon the direction of measurement (orientation of the bedding plane) as well.

Hence it becomes all the more important to have flexibility while choosing the value of *m* for S_w computations.

Theory

The present study attempts an improvement in terms of *a*, *m*, *n* values in the saturation equation proposed by Aguilera. The study has also incorporated effects of dipping beds as well as bore hole inclination on resistivity response of conventional tools. Though laminated shale layers are generally thinner than the adjacent sand layers, the clay constituents contribute a disproportionate change in resistivity and porosity on the latter. Petrophysical and reservoir properties between each layer may vary because of changing proportions of clays within each lamination. However, Asquith (1990) has discussed in great detail to show that because of their detrital origin, shale laminations between sands normally have the same clays and water content as adjacent thick shale beds. This similarity leads to the assumption that resistivities of laminated shale will be similar to those of adjacent thicker shale's. Therefore, in log analysis equations that require clay resistivities, the resistivity of adjacent shale's can be used to represent that of the shale in the shaly sand.

Case I. Tool axis perpendicular to the formation

In this case measurement axis of the tool is parallel to the formation layers and hence if vertical resolution of the tool is of the extent to include alternations of sand shale layers, the recorded resistivity will be equivalent to the shale and sand resistances stacked in parallel within a unit cube.

Thus the recorded resistivity R_t will be given by

$$\frac{1}{R_t} = \frac{V_{sh}}{R_{sh}} + \frac{V_{sd}}{R_{sd}},$$

Where

V_{sh} = shale volume per unit volume of the formation

Rsh = Resistivity of shale

V_{sd} = Sand volume per unit volume of the formation = $(1 - V_{sh})$

R_{sd} = Resistivity of sand

Thus, $$\frac{1}{R_{sd}} = \left(\frac{1}{R_t} - \frac{V_{sh}}{R_{sh}}\right)\left(\frac{1}{(1-V_{sh})}\right).$$

For clean sand, saturation estimation is quite accurately done by Archie's equation and therefore

$$S_w^{\,n} = \frac{aR_w}{\phi_{sd}^{\,m} R_{sd}},$$

$$\phi = \phi_{sd}(1 - V_{sh})$$

$$S_w^{\,n} = \frac{aR_w}{\phi^m R_{sd}}(1 - V_{sh})^m \tag{1}$$

$$= \frac{aR_w}{\phi^m}\left(\frac{1}{R_t} - \frac{V_{sh}}{R_{sh}}\right)(1 - V_{sh})^{m-1}. \tag{2}$$

Poupon et. al. (1954) derived the same formula using *m*=2 and *n* = 2

Thus his equation was

$$S_w^{\,2} = \frac{aR_w}{\phi^2}\left(\frac{1}{R_t} - \frac{V_{sh}}{R_{sh}}\right)(1 - V_{sh}).$$

Roberto Aguilera (1990) made a generalization over Poupon by replacing exponent of Sw with n and exponent of ϕ with m in the above formulae and thus used m-1 that did not appear in the Poupon's formulae.

The equation according to Aguilera is

$$S_w^{\,n} = \frac{aR_w}{\phi^m}\left(\frac{1}{R_t} - \frac{V_{sh}}{R_{sh}}\right)(1 - V_{sh}).$$

Equation (2), an improvement over Aguilera's equation, can be used in most of the fields of western India where *m* is taken as 2.15. If shaliness is around 30% the correction in *Sw* values is approximately 5% and if shaliness is of the order of 20% the correction in saturation value will be about 3%. Thus it is realized that the correction incorporated with proper generalization is very significant. In case of laminated reservoirs, equation 1 will yield more realistic saturation values than the ones calculated by other formulae.

Case II. Tool axis not perpendicular to the formation

This situation arises (i) when the well is inclined (ii) and/or the beds are dipping. Both the conditions warrant corrections to arrive at a representative resistivity value. This is attempted by considering R_H – the resistivity in the direction parallel to the layer and R_V – the resistivity in the direction perpendicular to the layer and solving for R_{sd} as follows. The potential drop in parallel direction will be $R_H I \cos\delta$ and potential drop in perpendicular direction will be $R_V I \sin\delta$ where, I is the measuring current and δ is the angle subtended by the axis of measurement of the tool with formation layers.

Thus, $IR_t^{\,2} = (IR_H \cos\delta)^2 + (IR_V \sin\delta)^2$,

which implies $R_t^{\,2} = (R_H \cos\delta)^2 + (R_V \sin\delta)^2$.

R_H is given by

$$\frac{1}{R_H} = \frac{V_{sh}}{R_{sh}} + \frac{V_{sd}}{R_{sd}}.$$

R_V is given by

$$R_V = V_{sh}R_{sh} + V_{sd}R_{sd}.$$

Thus,

$$R_t^{\,2} = \left[\frac{R_{sh}R_{sd}\cos\delta}{\left(V_{sh}R_{sd} + (1-V_{sh})R_{sh}\right)}\right]^2 + \left[\left(V_{sh}R_{sh} + V_{sd}R_{sd}\right)\sin\delta\right]^2$$

To a first degree of approximation R_{sd} appearing in the denominator of the first term can be approximated to be equal to R_t the measured resistivity and thus the above equation can be expressed as a quadratic equation in R_{sd} of the form

$$aR_{sd}^{\,2} + bR_{sd} + c = 0$$

where

$$a = \left[\frac{R_{sh}\cos\delta}{\left(V_{sh}R_t + (1-V_{sh})R_{sh}\right)}\right]^2 + \left[(1-V_{sh})\sin\delta\right]^2$$

$$b = 2V_{sh}R_{sh}(1-V_{sh})\sin^2\delta\,, \quad \text{and}$$

$$c = (V_{sh}R_{sh}\sin\delta)^2 - R_t^{\,2}.$$

Therefore we have

$$R_{sd} = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \tag{3}$$

a, b, c have to be computed from the above equation and finally it leads to the computation of R_{sd}. The value has to be substituted in equation (1) for estimation of.

Application of the formula on field examples

For this study, well log data has been interpreted for zones with laminated shale-sand sequences, which are validated by geological studies and core data analysis. Interpretation results using Multi mineral model have been used for porosity values and standard values for a, & m viz., 0.62, & 2.15 taken. Using parallel resistivity formulae, the resistivities of sand layers in the laminae are evaluated and using Equation (2), Sw values are computed for vertical wells. These are illustrated as Case-I in the tables and paralogs shown below. For inclined well/ dipping formations,the angle between formation layer and the measurement axis of the tool has been taken as 15 degrees and the resulting Rsd values have been used in Equation (1) for arriving at the Case II Sw values

Illustrative Tables

Table-1: Calculated water saturations from Well A, Cambay Basin Calculations assume R_w=0.18 ohm-m, R_{sh}=3.0 ohm-m.

Zone	ϕ	R_t	V_{sh}	S_w (Proposed model) Case I	S_w (Proposed model) Case II	Sw (Multi mineral)
1	0.26	4.0	0.23	0.51	0.52	0.61
2	0.27	2.0	0.18	0.81	0.81	0.77
3	0.21	6.0	0.20	0.50	0.53	0.59
4	0.23	6.0	0.20	0.45	0.48	0.60
5	0.22	6.5	0.17	0.48	0.50	0.56

Table-2: Water saturations from Well B, Cambay Basin. Calculations assume R_w=0.14 ohm-m (intervals 1, 2 & 3) and 0.18 ohm-m (intervals 4 &5), R_{sh}=3.0 ohm-m.

Zone	ϕ	R_t	V_{sh}	S_w (Proposed model) Case I	S_w (Proposed model) Case II	Sw (Multi mineral)
1	0.22	4.5	0.31	0.42	0.44	0.54
2	0.24	5.0	0.24	0.40	0.42	0.50
3	0.23	2.0	0.23	0.80	0.80	0.83
4	0.22	5.5	0.31	0.38	0.43	0.49
5	0.20	5.0	0.24	0.56	0.58	0.62

Table-3: Calculated water saturations from Well C, Cambay Basin Calculations assume R_w=0.19 ohm-m, R_{sh}=2.0 ohm-m.

Zone	ϕ	R_t	V_{sh}	S_w (Proposed model) Case I	S_w (Proposed model) Case II	*Sw* (Multi mineral)
1	0.27	6	0.04	0.52	0.53	0.56
2	0.19	7	0.20	0.37	0.50	0.58
3	0.24	7	0.12	0.43	0.46	0.55

Discussions

In case of vertical well or when the formation layers are perpendicular to the well bore, the value of *Sw* computed as per the proposed model is significantly lower than the one computed with the help of multi mineral model. This may explain the production scenario in some of the wells, which appear to be more than expected.

Computation with assumed angle of 15 degree between the formation layers and measurement axis of the tool indicates marginal increase in *Sw* values in most of the cases.

The interval, which appears as water bearing in Multi mineral analysis, appears the same in the present study as well.

Illustrative Paralogs

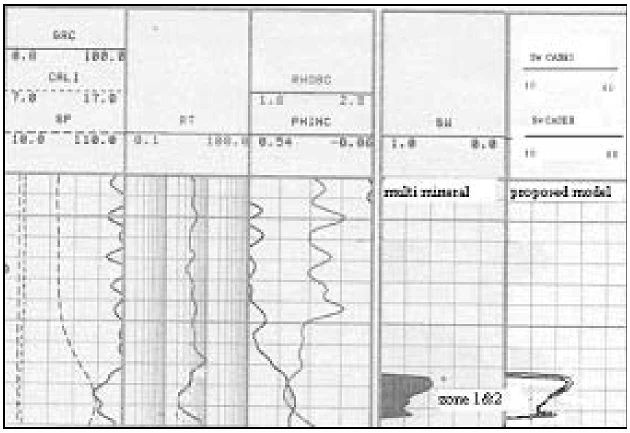

Fig. 1: Paralog of Well A showing zone 1&2

Conclusions

The present study aims to derive the true resistivity in laminated sand- shale sequence thereby attempting to achieve realistic saturation estimations.

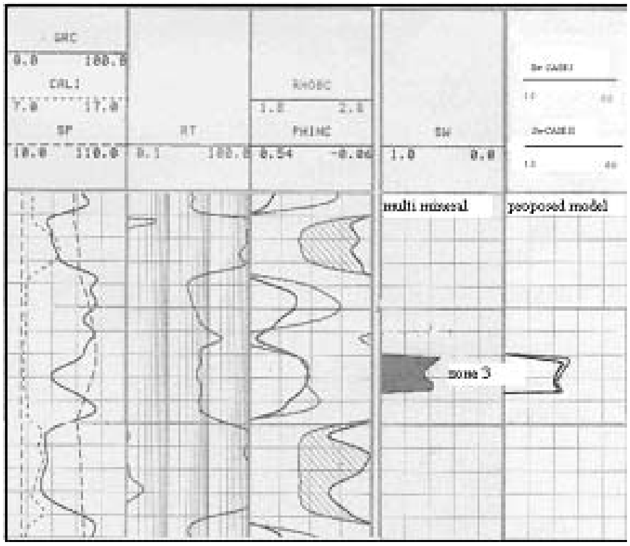

Fig. 2: Paralog of Well A showing zone 3

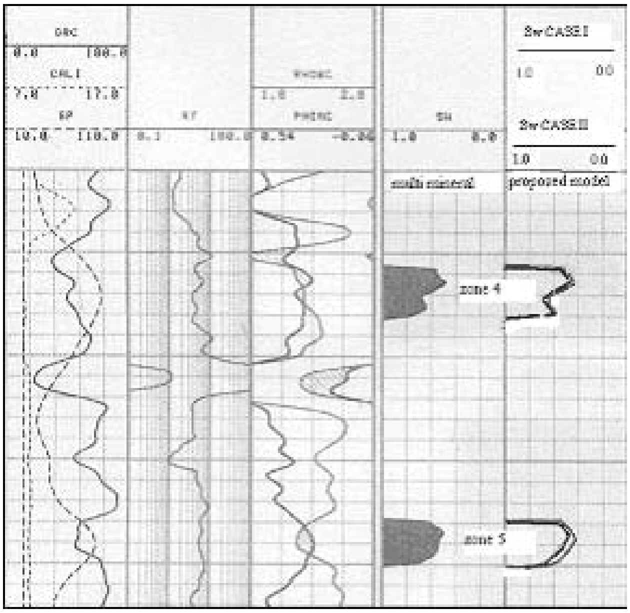

Fig. 3: Paralog of Well A showing zone 4&5

An improvement in the computation using formula proposed by Aguilera has been attempted.

A method for computation of resistivity has been developed
for the case where, the axis of measurement of the tool is not parallel to the formation layers.

Significant improvement in oil saturation values in laminated reservoirs, as shown by this study, will result in

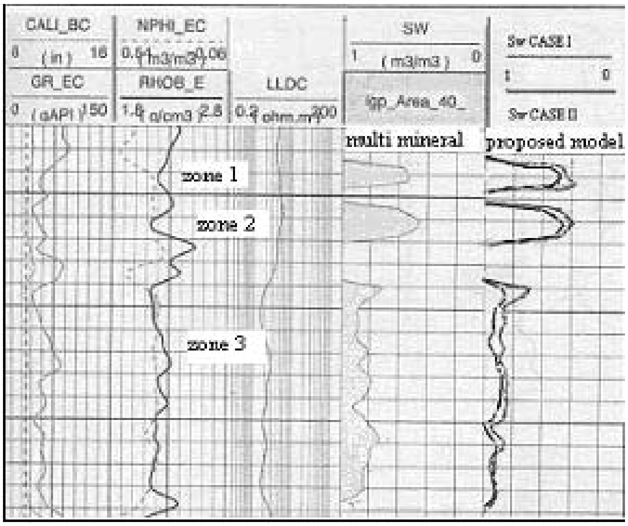

Fig. 4: Paralog of Well B showing zone 1,2&3

upward revision of reserves, which could serve as a tool for mitigating the exploration risks.

Acknowledgements

The authors are grateful to ONGC and the ED – Asset Manager, Mehasana Asset for giving permission to publish the paper. The authors are also indebted to ED – Chief Logging Services for his encouragement. Also acknowledged is the Sub Surface Manager, Mehsana Asset for extending all help to carry out the study. The authors would like to mention with gratitude the facilities and data provided for the work by the Well Logging Services, Mehsana and the Interpretation Group, WLS, Baroda.

Views expressed in this paper are those of the authors only and may not necessarily be of ONGC.

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