Estimation of Resistivity Anisotropy, Vertical Resistivity and Permeability in Low Resistive Eocene Laminated Reservoir of Cauvery Basin: A Case Study

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Keywords

Laminated Reservoir, Resistivity Anisotropy, Resistivity of Sand, Vertical Resistivity

Abstract

Laminated shaly sand sequences are deposited in all types of sedimentary depositional (continental, transitional and marine) environment. These shaly sand reservoirs are alternating thin layers of sand and shale where the thickness of the individual layer is less than the vertical resolution of conventional logging tools. The measured apparent resistivity by the conventional logging tool provides the average resistivity of these laminations which is dominated by conductive layers. These laminated sequences may contain large amount of hydrocarbon. However, interpretation of these kinds of reservoirs is quite difficult.

The study proposes an unconventional method to estimate coefficient of resistivity anisotropy (λ), horizontal resistivity (R_h) and vertical resistivity (R_v) using conventional logs in low resistive laminated shaly sand sequences. Resistivity anisotropy is modelled by using plot of apparent resistivity against relative dip. The angle between the borehole axis and the direction normal to the laminated reservoir for a deviated borehole in a dipping laminated reservoir is known as the relative dip angle. As relative dip increases the conventional measurement is equivalent to a combination of horizontal and vertical resistivity. In this method field is divided into smaller areas where formation shows similar kind of behavior. The parallel resistor model applied when there is low relative dip angle between tool and formation. A total of 12 wells have been considered for study. These wells are drilled with different deviation angles and covering a vast area of the reservoir of this sub-basin. R_h and R_v curves are estimated from conventional apparent resistivity and resistivity anisotropy. This is followed by, estimation of R_h and R_v with the help of Moron and Gianzero (1979) formula and then calculating sand resistivity (R_{sd}) using parallel and series electrical connections. These measurements are then used in Laminated Shaly Sand Analysis (LSSA) technique.

The predicted permeability using the proposed methodology matches nicely with the core permeability. A comparison was also drawn with permeability obtained in reservoir studies. It was observed that the predicted permeability calibrates well with the permeability obtained in reservoir studies. Due to practical application and robustness of the method, it can provide us a potential petro physical evaluation tool to determine sand characteristics more accurately for laminated shaly sand reservoirs.

Introduction

Thin layers of allogenic clay/shale get deposited between the clean sand layers due to multiple cycle of deposition under a dual flow regime. These shale laminations do not disturb the characteristics of the surrounding clean sand streaks. The conventional resistivity logging tools (Induction/Laterolog) measure almost equivalent response against the thinly bedded sequences as it measures against the shale or homogenous low resistive formation, even if the sand lamina is resistive. Major limitation in such instances is the resolution of the tool. In case of highly deviated wells, measured apparent resistivity is affected by the relative deviation angle. Therefore the angle between axis of the logging tool and the bedding is crucial for this type of analysis (Elhadidy et al., 2020).

Methodology

This study follows Moron and Gianzero equation which states that the measured apparent resistivity (R_a) is dependent on vertical (R_v), horizontal resistivity (R_h) and relative dip or bed inclination (θ) in the homogeneous anisotropic formation (Moron et al., 1979).

$$\mathbf{R_a} = \frac{\boldsymbol{\lambda} \mathbf{R_h}}{\sqrt{\boldsymbol{\lambda}^2 \cos^2\boldsymbol{\theta} + \sin^2\boldsymbol{\theta}}}$$

Where,

$$\boldsymbol{\lambda} = \sqrt{\frac{\mathbf{R_v}}{\mathbf{R_h}}}$$

In case of deviated boreholes, the current generated by the conventional induction tool passes through the thin bedded sequences. Due to the anisotropy in resistivity, the measured resistivity is known as apparent resistivity (R_a).

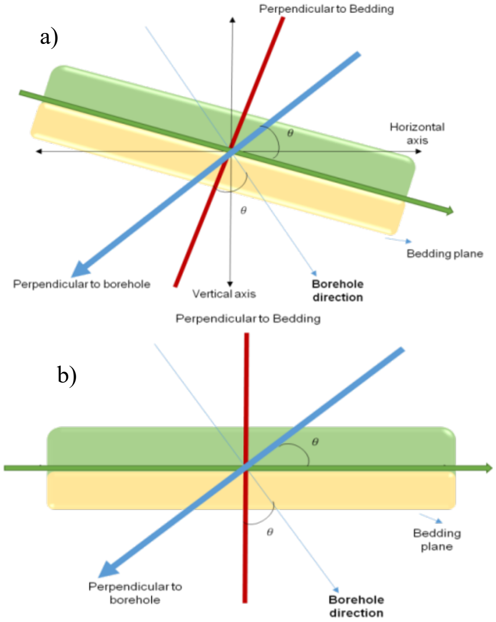


Figure-1(a): Inclined borehole and bedding sequences
Figure-1(b): Inclined borehole and horizontal bedding sequence

If θ=0 (For e.g., a vertical borehole passes through a horizontally thin bedded sequence), the measured resistivity is equivalent to the horizontal resistivity **(Figure-1)**. In general, shale shows a degree of electrical anisotropy, such that apparent shale resistivity depends on horizontal ($R_{sh,H}$) and vertical resistivity ($R_{sh,V}$). In case of vertical borehole, when current passes through parallel to the horizontal thin bedded sequence, the beds behave as a parallel resistor circuit and the horizontal resistivity can be obtained by using Kirchhoff's law (Kuriawan et al., 2005).

$$\frac{\mathbf{1}}{\mathbf{R_h}} = \frac{\mathbf{F_{sd}}}{\mathbf{R_{sd}}} + \frac{\mathbf{F_{sh}}}{\mathbf{R_{sh,H}}}$$

Where,

$$\mathbf{F_{sd}} + \mathbf{F_{sh}} = \mathbf{1}$$

F_{sd} = Sand volume fraction, v/v
F_{sh}= Shale volume fraction, v/v
R_{sd} = Resistivity of sand layers, ohm.m
$R_{sh,H}$ = Horizontal resistivity of shale layers, ohm.m

On the other hand, if the electric field applied perpendicular to the bedding sequences, the beds behaves as series resistor circuit and vertical resistivity can be obtained by the following equation:

$$\mathbf{R_v} = \mathbf{F_{sd}} \mathbf{R_{sd}} + \mathbf{F_{sh}} \mathbf{R_{sh,V}}$$

Hagiwara (1997) stated that shale layer resistivity can be obtained from massive shale section above or below the thinly bedded sequences. If the shale layers are microscopically anisotropic then the sand resistivity is obtained by:

$$\mathbf{R_{sd}} = \mathbf{R^0_{sd}} \left\{ 1 + \frac{1}{2} \left[\frac{\mathbf{R^0_{sd}}}{\mathbf{R_{sh,H}}} - 1 - \sqrt{\left(\frac{\mathbf{R^0_{sd}}}{\mathbf{R_{sh,H}}} - 1 \right)^2 + \frac{4\,\mathbf{R^0_{sd}}}{\mathbf{R_{sh,H}}} \left(\frac{\mathbf{R_{sh,V}}}{\mathbf{R_{sh,H}}} - 1 \right)} \right] \right\}^{-1}$$

Where,

$$\mathbf{F_{sd}} = \frac{\mathbf{R_v} - \mathbf{R_{sh,V}}}{\mathbf{R_{sd}} - \mathbf{R_{sh,V}}} \quad \text{And} \quad \mathbf{R^0_{sd}} = \mathbf{R_h} \frac{\mathbf{R_v} - \mathbf{R_{sh,V}}}{\mathbf{R_h} - \mathbf{R_{sh,H}}}$$

The assumption is that all sand and shale layer in the sequence are identical to each other.

Analysis

Cauvery basin evolved in late Jurassic period as a result of rift-drift phenomenon of the Indian plate from Gondwanaland. This basin is divided into 5 sub basins due to formation of graben and horst blocks. The present study is confined within the Nagapattinam sub-basin. This sub-basin consists of multi-layered hydrocarbon pay sands within the K formation belonging to Paleocene and Eocene Epoch **(Figure-2)**.

A total of 12 wells have been considered for study **(Table-1)**. These wells are drilled with different deviation angles and covering a vast area of the reservoir of this sub- basin. Conventional data of these wells have been taken to estimate vertical, horizontal resistivity, macroscopic anisotropy, true sand resistivity and Permeability. Conventional data includes GR, Induction deep resistivity, and Neutron-Density logs. Calculated shale volume using GR log is used to determine continuous log curves of R_h and R_v. Well W1 is having the Tri-axial data which is used for validation of calculated Vertical and Horizontal resistivity.

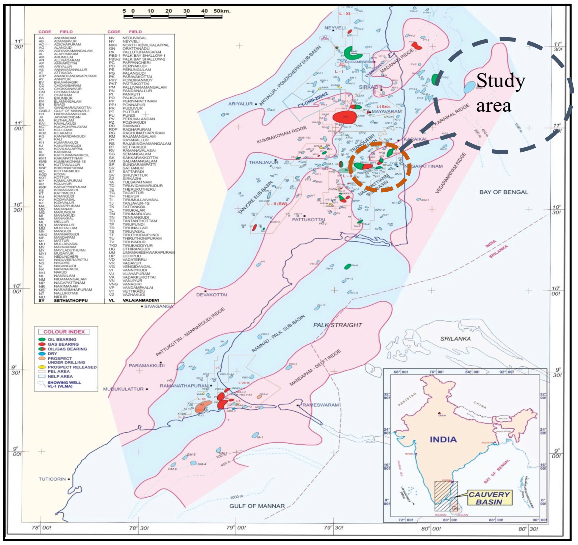


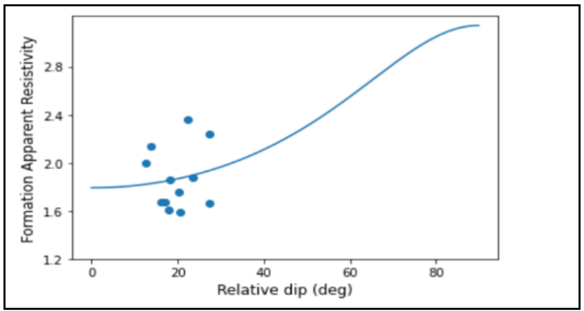
Figure-2: Prospect map of Basin

Wells	Relative Dip (Deg)	Formation Apparent Resistivity (ohm.m)	Shale Apparent Resistivity (ohm.m)
W1	18.2	1.86	0.8
W2	29.3	1.92	0.84
W3	22.2	2.36	0.756
W4	27	2.37	0.95
W5	27.2	2.24	0.74
W6	12.5	1.996	0.82
W7	16	1.67	0.71
W8	27.4	1.66	0.87
W9	18	1.61	0.82
W10	23.5	1.88	0.82
W11	20.5	1.59	0.9
W12	20.4	1.756	0.78

Table-1: Relative dip, Formation apparent resistivity and Shale apparent resistivity of wells considered for study.

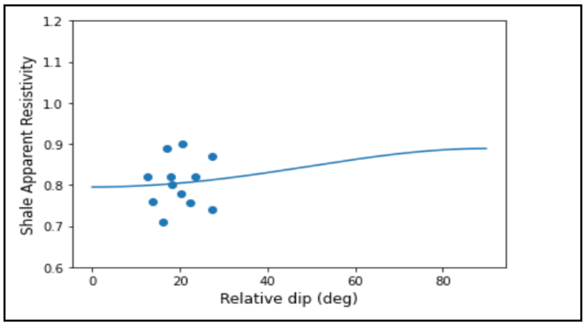
After the correlation of wells, the measured apparent formation resistivity and deviation angle against the target intervals (relative dip) are listed together in **Table-1**. The mean resistivity value should be averaged among intervals and having the same shale reservoir facies.

In this study, it has been assumed that the reservoir beds are near orthogonal to well trajectory. Apparent resistivity and relative dip is plotted for all the listed data points and the curve fitting process is applied using the equation of Moron and Gianzero (1979). The non-linear least square curve fitting method is used to determine the best fit of the data points **(Figure-3)**. Total error between the data points and the curve can be minimized by varying the values of $R_h$andR_v. The output from this step gives an estimate of R_h and R_v for the formation at the given volume of shale. For the monotonous shale section, same curve fitting method is applied against the plot of apparent shale resistivity and relative dip. It shows that shale section is also having the anisotropy. This step determines the values of $R_{sh,H}$ and $R_{sh,V}$ for the formation. It has been assumed that shale properties are equivalent in target laminated reservoir and overlying massive shale column.



λ = 1.76, R_h = 1.791 ohm.m, MSE=0.064

Figure-3(a): Plot against formation apparent resistivity and relative dip using least square method



λ_{sh} = 1.12, $R_{sh,H}$ = 0.795 ohm.m, MSE =0.069

Figure-3(b): Plot against Shale apparent resistivity and relative dip using least square method

The estimated horizontal and vertical resistivity of the formation is equivalent to 1.79 and 5.52 ohm.m, respectively in thin bedded sequences encountered in the Eocene reservoir. Same procedure is applied for the shale section and observed resistivity anisotropy is 1.12. The values of $R_{sh,H}$ and $R_{sh,V}$ are 0.79 and 0.99 ohm.m, respectively.

The estimated mean squared errors are 0.064 and 0.069 for formation resistivity and shale column resistivity, respectively. These values are estimated against the interested zone with pre-defined average shale volume of 45%. After the determination of R_h, R_v, $R_{sh,H}$ and $R_{sh,V}$ from the anisotropy plot, continuous log of R_h and R_v can be estimated by using Kirchoff's law.

Comparison between conventional and laminated shaly sand analysis module

The modelled R_h and R_v values in well W1 have been validated with the tri-axial resistivity log in track 4 **(Figure-4)**, recorded in the recent well in the Nagapattinam sub-basin against the Eocene shaly sand reservoir and found within the tolerance limit.

The mean squared error between the estimated vertical resistivity from current study and recorded Tri-axial vertical resistivity is 2.809. Further, sand resistivity, water saturation and other petro physical parameters have been calculated against the target laminated reservoir.

However, Thomas Stieber Cross-plot (Total porosity vs Shale volume) is matching with calculated resistivity (R_h and R_v) and tri-axial data **(Figure-5)**. The Thomas Stieber technique distributes the shale content into laminar, dispersed and structural. Formation structure has no impact on V_{sh} and total porosity because they are scalar measurement. This means that if sand and shale are present in the formation, whether in extensive laminae or deformed in any way, they will always appear on the 'laminar shale' line on the Thomas Stieber plot (Aldred et al., 2017).

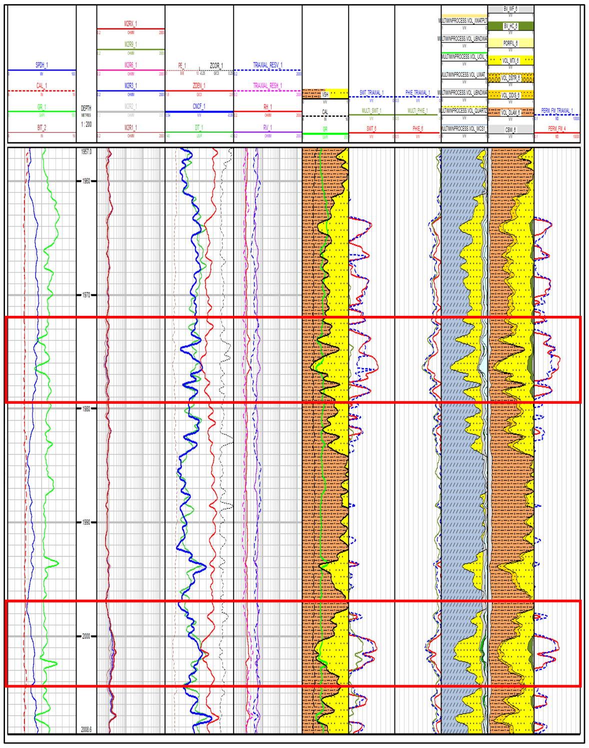


Figure-4: Validation of modelled R_h and R_v values.

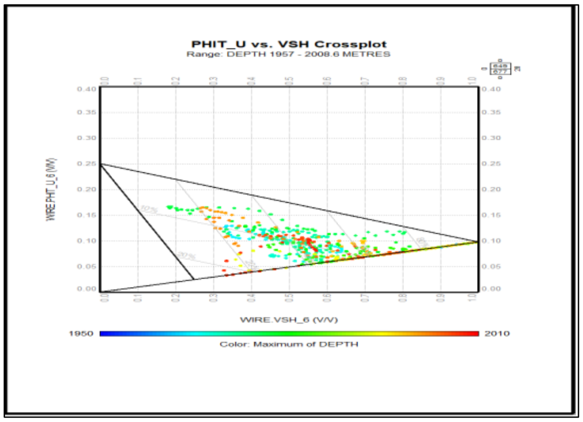


Figure-5(a): Thomas Stieber plot by calculated R_h, R_v

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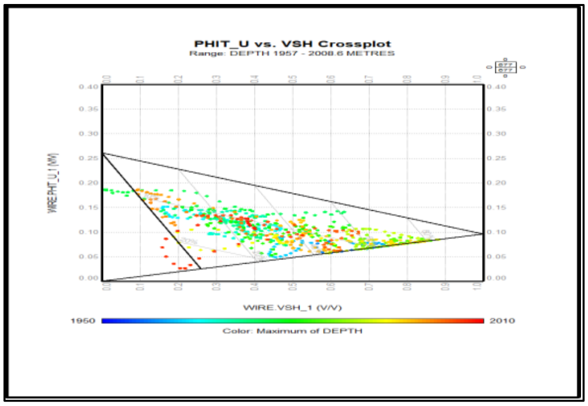

Figure-5(b): Thomas Stieber plot by Tri-axial data

Model Validation with core permeability and measured permeability in other wells

The effective porosity of sand fraction could only be a laminar sand volume when there is no effective porosity in shale. The estimated permeability index from the laminar sand properties may be significantly greater than those calculated from bulk effective porosity (Mollison et al., 1999). In this module, Modified Timur Permeability Index equation is used for permeability estimation in clean sand.

Model Applied on Well A

This model is populated to the nearby well A, where the core permeability has been estimated from laboratory. The horizontal and vertical resistivity is predicted for this well and used into the LSSA module to predict formation permeability. Conventional core has been taken in this well in the study interval. Permeability has been estimated at depth of 1959.4 m and 1959.42 m, the estimated laboratory permeability values are 107.103 mD and 139.794 mD, respectively. Laboratory estimated permeability (black point data) and modelled permeability from LSSA technique is shown in track-7 **(Figure-6)**. It can be observed that the predicted permeability from the LSSA method devised in the current study and permeability obtained in the core study match well.

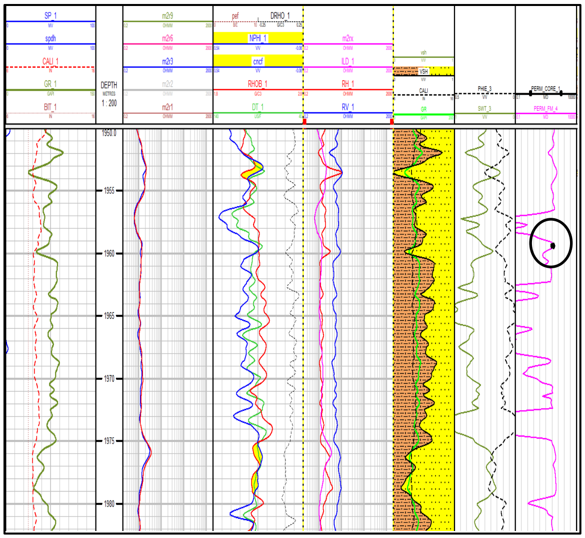

Figure-6: Model validation with core permeability and estimated permeability in well A.

Model applied on Well B

Again this model is populated in well B for comparison between estimated permeability from model and through reservoir study. Both the values are almost same **(Figure-7)**. The interval 2013-2006 m was perforated and reservoir studies were carried out. The permeability as estimated in reservoir studies was about 65.7 mD against the perforated zone (black point data in track 7). The permeability modelled through current method was found to be in agreement with the estimated permeability from reservoir studies as shown in figure-7.

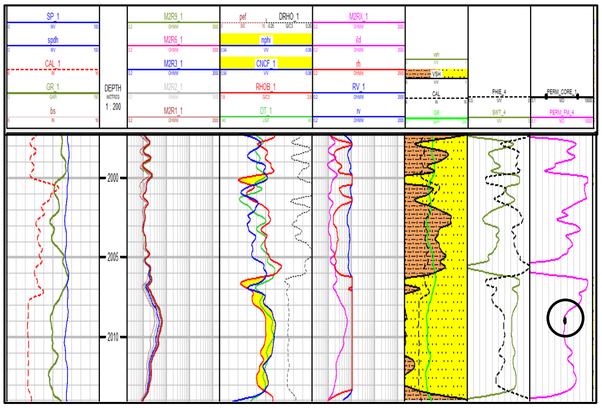

Figure-7: Model validation with permeability through reservoir study and measured permeability in well B

This unconventional model as proposed in the present study estimates sand resistivity, effective porosity, and water saturation. Additionally, the Modified Timur Permeability Index equation evaluates formation permeability which matches with the permeability estimated from Tri-axial data in well W1 (Figure-4), core permeability in well-A, and permeability estimated by reservoir study in well-B.

Conclusion

Sand resistivity has been estimated in laminated shaly sand sequences utilizing the parameters viz. effective dip angle, sand fraction, shale resistivity and shale anisotropy. More accurate predictions of permeability have been done using this unconventional approach.

Study shows that the values of shale volume play crucial role, especially at smaller dip angle, and the calculated parameters can be used to re-evaluate petro physical outputs against the laminated shaly sand reservoirs. The model presented in this study has the ability to identify low resistive pay zones and can further strengthen interpretation techniques.

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Disclaimer

All views expressed in the paper belong to the authors only and not necessarily represent the view of the ONGC.

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