PaperID **AU429**
Author **Manoj Kumar , ONGC Ltd. , India**
Co-Authors **J P Dobhal, Dr. Ashok Soni, Sujay Thakur**

Permeability estimation from Stoneley wave slowness for complex lithology shaly sand reservoir: A case study of Linch Field, Western onland Basin, India

Abstract

Permeability is one of the most important characteristics of hydrocarbon bearing formations. It is often measured in the laboratory on core samples or evaluated from well test data. If the sufficient core permeability data are available, relationships between porosity and permeability can be derived through regression analysis but in case of fewer core permeability data we need an innovative methodology to estimate the reservoir permeability. This paper presents an innovative methodology to estimate the permeability from the Stoneley wave slowness. Stoneley waves are most commonly generated during borehole sonic logging. They propagate along the walls of a fluid-filled borehole. They make up a large part of the low-frequency component of the signal from the seismic source and their attenuation is sensitive to fractures and formation permeability. Therefore, analysis of the Stoneley wave slowness is a useful approach to estimate formation permeability.

The area under study comprises the Linch pays of older Cambay Shale formation, Western on land basin India. The reservoir pays (Linch Pays) are complex lithology Shaly, Silty discrete Sand layers with limited lateral extent. The drilled wells in the study area have a good quality conventional logs data. Stoneley wave slowness data is available only for 4 wells. Multi-Resolution Graph-Based Clustering (MRGC) methodology, in which model locates clusters using a multi-dimensional dot-pattern recognition method based on non-parametric k-nearest neighbors and graph data representation is used to estimate the Stoneley slowness data for the other wells from conventional logs like, density, neutron, compressional slowness and gamma ray log.

To estimate the permeability from Stoneley slowness, the first step includes modeling of Stoneley wave slowness in non-permeable zones (DTSTE). In next step Stoneley permeability index (STPI) is determined by calculating the ratio between measured Stoneley slowness (DTST) and modeled Stoneley slowness for non-permeable zones (DTSTE). Finally the permeability is estimated by employing the index matching factor (IMF) and Stoneley permeability index (STPI) (Winkler & Johnson, 1989).

The core permeability from special core analysis of 6 wells is integrated to compare/validate the estimated Stoneley permeability. The estimated Stoneley permeability agrees well with those derived from core analysis and CMR log. The results of this study show that this innovative methodology is an effective tool for estimation of permeability of a complex lithology Shaly, Silty Sand reservoir layers of the studied area and this methodology can also be extended to the other fields of the Basin.

Introduction

Linch field was discovered in 1972 when LU-I unit produced oil. This field is located (Fig.-1) on the western rising flank of Warosan low in the south-east part of Mehsana sub-block in the Mehsana-Ahmedabad block of Cambay Basin. It is an anticlinal structure trending in NW-SE direction and lies between two very prominent tectonic elements, Mehsana Horst in the west and Jotana Fault in the east. In fact Mehsana Horst remained a positive area throught during deposition of Cambay Formation and did restrict the deposition of OCS sediments to the west. Linch field is surrounded by Nandasan in the east, North Kadi in the west, Jotana to the north and South Kadi to towards south, all four being major oil producing field. Petroleum system of the field is well defined. Organically rich thick older cambay shale is attributed to be the main source rock. The depressions Warosan Low and Nardipur low are believed to be the main kitchen for hydrocarbon generation. Sand/Silt layers found within OCS, Kadi formation and Kalol formation provide multilayered reservoirs. Various arenaceous units within OCS, designated as Linch pays occur as discreet lensoid sand body having limited aerial extent. Linch pays are mainly dominated by thick dark grey shale. Shale is often inter-layered by hard, very fine grained sideritic and thin carbonaceous laminate. Core study reveals that Quartz is the major framework mineral with Siderite and traces of Feldspar and pyrite. Illite, Kaolinite and Chlorite are the main clay minerals.

Methodology

In the present study, a four-step approach is followed for permeability estimation from acoustic data as follows

I. Prediction of the Stoneley wave slowness from conventional logs using a Multi resolution graphical based cluster (MRGC) technique.
II. Modeling of the Stoneley wave slowness in non-permeable zones,
III. Calculation of the Stoneley permeability index, and
IV. Calculation of the permeability by employing the index matching factor and Stoneley permeability index.

Stoneley wave slowness from well logs

In this section, Multi-Resolution Graph-Based Cluster (MRGC) methodology was adopted to estimate the Stoneley wave slowness from conventional logs data.

MRGC is a multi-dimensional dot-pattern recognition method based on non-parametric k-nearest neighbors and graph data representation. The underlying structure of the data is analyzed and natural data groups are formed that may have very different densities, sizes, shapes, and relative separations. MRGC automatically determines the optimal number of clusters, yet allows the operator to control the level of detail actually needed to define the electrofacies.

As mentioned earlier, the Stoneley wave slowness data were only available for 4 wells. The MRGC model include gamma ray log (GR), sonic log (DT), density log (RHOB), and neutron porosity log (NPHI). The input and output data were normalized in the range of 0 and 1. The optimal parameters of the MRGC model were achieved by trial and error. The cross plot of the measured and predicted Stoneley wave velocity in the testing samples is shown in Fig.-2 and Fig.-3.

In the light of the acceptable results of the MRGC model, DTST is predicted by using the conventional well log data for the other wells of the study area.

Stoneley wave slowness in non-permeable zones (DTSTE)

The Stoneley slowness can be modeled for a non-permeable formation as follows:

$$\mathrm{DTSE} = (\mathrm{DFD} * \mathrm{DTSM2RHO}) + \mathrm{DTF2})$$

Where, DFD is Drilling fluid density, $DTSM$ is formation shear slowness, RHO is formation density and DTF is drilling fluid slowness.

If the drilling fluid properties DFD and/or DTF are not known, a cross plot of $\mathrm{DTST2}$ D versus $\mathrm{DTSM2}/RHO$ can be used to estimate these parameters. When drawing a line on this cross plot trough the non-permeable points (the shale line), then the slope of this line is DFD and the intercept is $\mathrm{DTF2}$.

Stoneley permeability index (STPI)

Stoneley permeability index is determined by calculating the ratio between a measured Stoneley slowness (DTST) and a modelled Stoneley slowness for non-permeable formation.

$$\mathrm{STPI} = \mathrm{DTSTDTSTE}$$

Where STPI is the Stoneley permeability index, DTST is the Stoneley wave slowness of formation, and DTSTE is the Stoneley wave slowness modeled for non-permeable zone.

The Stoneley permeability index, STPI, is not an estimation of permeability, but it is an index of fluid movement in porous media around the borehole.

Stoneley permeability

Since fluid movement is a function of pore throat distribution, pore shape, and pore size, the Stoneley permeability index is a tortuosity index only. These factors can be combined in a concept called Stoneley Flow Zone Index (SFZI).

$$SFZI=IMF(STPI-1)$$

Where, SFZI is Stoneley flow zone index and IMF is flow zone index matching factor, which is the sum of the volume weighted IMF for each individual mineral in the formation.

After conversion of STPI to SFZI the Stoneley permeability (KSTONELEY) can be estimated based on the following relation. (Winkler & Johnson, 1989).

$$KSTONELEY=C*SFZI2(\Phi3\ 1-\Phi2\ )$$

Where, C is empirical calibration factor (default: 1014) and ϕ is effective porosity.

Discussion of Results

The technique as described above, has been used for permeability estimation of key wells of study area. The index matching factor (IMF) for Quartz=12, Silt=8, Shale/WCS=0, Coal=0 and default value (1014) for the empirical calibration factor(C)) are used. The estimated Stoneley permeability along with conventional logs are presented in next section and a comparison is made between estimated Stoneley permeability with core permeability and CMR log permeability.

(A) Comparison of Stoneley Permeability and core permeability

Conventional core analysis (CCAL) data is available for the Linch Pay of Well-A and Well-B. Graphical illustrations of Fig.-4 and 5 represent a comparison between the Stoneley (continuous red line) and core permeability (blue dots). Other rock properties including bore hole quality logs, porosity and lithology column are also displayed. As shown in figures 4 and 5, there is a good agreement between the Stoneley permeability and core permeability.

(B) Comparison of Stoneley Permeability CMR permeability

As mentioned earlier, CMR data is available for Linch Pay of Well-C from the studied field. The most important property of CMR measurement is the ability to record a continuous log of permeability. The Timur-Coates equation was used to calculate formation permeability (KTIM). Graphical illustrations of Fig.-6 represent a comparison between the Stoneley (continuous red line) and CMR permeability (KTIM-continuous blue line)

The cross-correlation of CMR and Stoneley permeability for Well-C shows a good agreement between the

Stoneley wave slowness and CMR permeability. Unfortunately, there is no measured core porosity and permeability data for well C to assess the reliability of the Stoneley and CMR methods. Nonetheless, it could be claimed that CMR logging and acoustic methods have different concepts and physics of measurement, but they reach close results for permeability estimation.

This could be a confirmation of permeability estimated from Stoneley slowness method used in this study. The Stoneley permeability estimated for Well-D is shown in Fig.-7.There is no measured core permeability data for Well-D to assess the reliability of estimated Stoneley permeability, but through the log correlation and nearby reservoir characteristics it could be claimed that Stoneley slowness method produced the reliable results

Conclusions

- In the present study, an innovative approach is successfully applied to estimate permeability by using Multi-Resolution Graph-Based Clustering (MRGC) methodology and Stoneley wave slowness data.
- Stoneley wave slowness in the framework of the Stoneley flow zone units approach provides high accuracy estimations of permeability for complex lithology shaly, silty sand reservoirs.
- The estimated permeability is validated through core permeability and CMR log permeability data.
- Multi-Resolution Graph-Based Clustering (MRGC) methodology is easier and faster in comparison to the Linear/Multiple Regression, to predict Stoneley wave slowness from conventional well logs.
- This methodology based on Multi-Resolution Graph-Based Clustering (MRGC) and Stoneley

wave slowness can also be extended to the other fields of the Basin.

Acknowledgement

The authors express their sincere gratitude to DIR (Exploration) and ONGC management for giving permission to publish this paper. The authors are extremely grateful to Shri Ashutosh Bhardwaj, ED-HOI-GEOPIC, for providing all infrastructural facilities and technical support. The views expressed in this paper are of the authors only and not necessarily of ONGC.

References

Buffin, A., 1996, Permeability from waveform sonic data in the Otway Basin, SPWLA 37th Annual Logging Symposium, June 16-19

Rastegarnia, M. and A. Kadkhodaie-Ilkhchi, 2013, Permeability estimation from the joint use of Stoneley wave velocity and support vector machine neural networks: A case study of the Cheshmeh Khush Field, South Iran, Geopersia 3(2), PP. 87-97

S.J. Ye, P. Rabiller, "A New Tool for electrofacies Analysis: Multi-Resolution Graph-Based Clustering", SPWLA, 41st Annual Logging Symposium Transaction, paper PP.

Winkler, K.W., Liu, H.L., Johnson, D.L. 1989. Permeability and borehole Stoneley waves: comparison between experiment and theory. Journal of Geophysics, 54: 66-75.