Enhanced Reservoir Description Using Hydraulic Flow Unit Concept for A Clastic Reservoir: A Case Study of Linch Pay, Linch Field, Cambay Basin, India

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Summary

The purpose of the present study is aimed to carry out Hydraulic Flow Unit (HFU) modeling for a clastic oil reservoir of Linch Pay, Linch Field, Cambay Basin. Linch pays of Older Cambay Shale of Early Eocene sequence are discrete sand bodies embedded in monotonous shale unit. Lithofacies and distribution pattern of clastic unit depicts eight subpays from LU-I to LU-VIII from top to bottom.This study involves rock type classification based on routine and special core analysis data, statistical methods such as histograms, probability plot and cluster analysis. Finally seven HFU's constituting the reservoir were identified based on calculations of Reservoir Quality Index (RQI) and Flow Zone Index (FZI). In addition to that three major rock groups were also identified based on core description.This study will help in understanding the heterogenity of Linch pay and also assist in reliable estimation of the permeability in uncored wells, generation of initial water saturation profiles and consequently reliable reservoir simulation studies.

Introduction

Reservoir characterization to understand storage and flow capacities of a reservoir by rock typing is essential for building a robust dynamic model leading to reliable reservoir prediction through proper reservoir simulation work. Discrimination of rock types based on litho facies and empirical relationship between log of permeability and porosity is often subjective as it is observed that for any porosity, with in a rock type, permeability can vary by several orders of magnitude which demands rock classification involving flow properties. Rock classification based on Hydraulic Flow Unit concept is significant as it unifies several theories involving reservoir rocks and fluids they contain. The concept of hydraulic flow unit was first introduced by Ebanks (1987, 1992) who defined a Hydraulic Unit (HU) as a mappable portion of a reservoir within which the geological and petrophysical properties that affect the fluid flow are internally consistent and predictably different from the properties of other reservoir volumes.The concept of HFU has been attempted for Linch pays of Linch Field, Cambay basin (Figure-1).

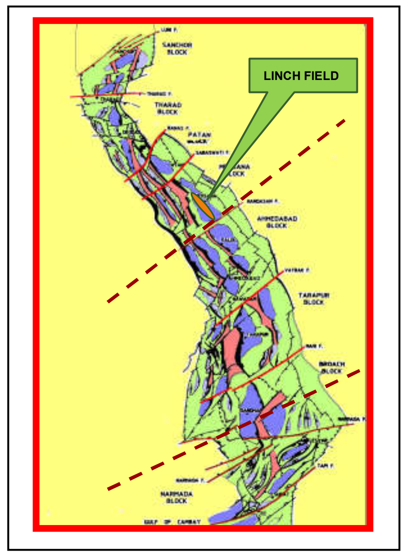


Figure 1: Tectonic Map of Cambay Basin showing Linch Field

Geological Setting and Stratigraphy

The Cambay Basin is an elongated and narrow intra-cratonic rift grabenoriented in North-South direction. The basin developed towards the end of Mesozoic due to development of tensional faults along N-S trending basement lineaments followed by outpouring of lava flow which formed technical basement i.e. Deccan Trap. The basin started rifting perpendicular to Eastern and Western margin faults which were parallel to axis of basin. A number of uplifts and depressions developed parallel to axial trend. As the rifting continued the longitudinal fault system developed both towards East and West, deriving sediments from uplifted block of Deccan Basalt. First sedimentation leads to deposition of Olpad formation in Alluvial fan complex followed by transgressive facies of OCS (older Cambay Shale). As rifting continued during Early Eocene time, the earlier generated faults reactivated and created more accommodation for deposition of Kadi formation (Mandhali and Mehsana Members). Kalol and Tarapur Formation rest conformably on Kadi Formation (Malviya et.al, 2008). Table 1 shows general stratigraphy along with gross lithology in Cambay Basin. Linch pays developed within the OCS.

Table-1: Startigraphy of Cambay Basin

Age		Formation/Member		Lithology
Pliocene to Recent		Gujrat Alluvium Jambusar Broach		Alluvium Kankar
E. Miocene to L. Miocene		Jhagadia Kand Babaguru		Mainly Claystone
Oligocene		Tarapur		Predominantly argillaceous section with dirty grey to greensih grey shale. Occasionally Sandstone and Siltstone
Eocene	Upper			
	Middle	Kalol		Sandstone, Siltstone with shale, coal and claystone
		Kadi	Upper Tongue	Grey to Dark Grey Shale
			Mehsana	Sandstone/Siltstone with dominantly coal
			Lower Tongue	Grey to Dark Grey Shale
	Lower		Mandhali	Shale with Siltstone/Sandstone
		Older Cambay Shale		Shale with Siltstone and Sandstone
Paleocene to Early Eocene		Olpad		Basalt
Late Cretaceous		Deccan Trap Group		

Rock Typing Methods:

Conventional method: Conventional method of rock typing involves simple regression evaluating permeability from log derived porosity based on correlation between core derived porosity and permeability. Figure 2 shows core derived permeability-porosity relationship for the entire Linch pay which indicate a moderate correlation between permeability-porosity. This moderate fitting and scatter of the data points could be attributed to the change in lithology with different fluid flow properties. Therefore it can be concluded that classical permeability-porosity plot may not give an accurate estimation of permeability from porosity and demands identification of rocks with similar fluid flow properties and group them to improve permeability-porosity correlation.

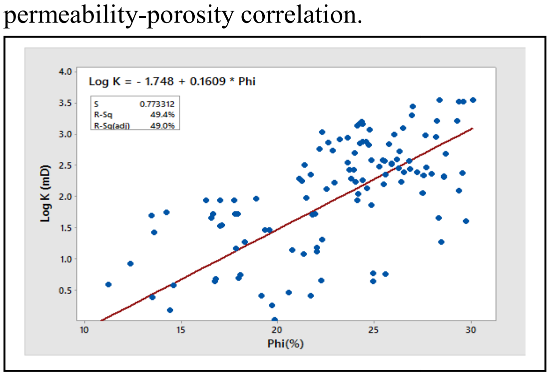


Figure 2: Permeability-Porosity Plot for Linch pay

Winland Method: This approach links perophysical properties such as porosity, permeability and capillary pressure to the pore-throat radius r_{35} (Gunter et al. 1997). Dale Winland of Amoco established an empirical relationship between porosity, permeability and pore throat radius from mercury intrusion tests (Spearing et. al 2001). This equation was later published by Kolodzie (1980) as

$$\log r_{35} = 0.732 + 0.588 \log K_{air} - 0.864 \log \phi \quad \text{.................... (1)}$$

Where r_{35} is the pore aperture radius corresponding to the 35^{th} percentile of mercury saturation, K_{air} is the air permeability (mD), and ϕ is porosity (%). The core samples of similar R_{35} values represent a single rock type and according to ranges of R_{35} different petrophysical rock types or flow units can be categorised as megaport (R_{35}>10μ), macroport (R_{35} between 2 and 10 μ), Mesoport (R_{35} between 0.5 and 2 μ), microport (R_{35} between 0.1 and 0.5 μ) and nanoport (R_{35}< 0.1 μ).

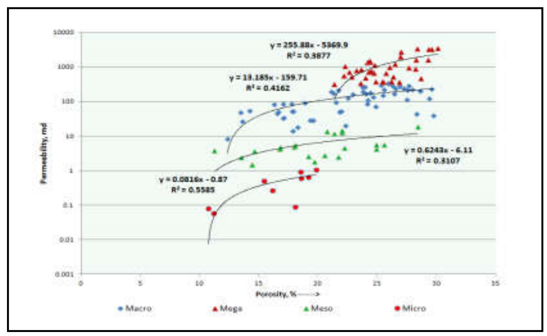


Figure 3: Winland Plot for Linch pay

Winland plot of all core sample data for Linch pay is shown in Figure 3 and it is evident from this plot that atleast four rock types are required to characterize Linch Pay.

Flow Zone Index Method: This method is governed by the physics of flow at pore scale and deals with calculation of two factors viz. Reservoir Quality Index (RQI) and Flow zone Index (FZI). A brief discussion on the theoretical part of this method is as follows (Amaefule, J.O et al, 1993, Abbaszadeh, M et. al.1995, Guo, G. et al. 2005 and Desouky S.E.D.M.2005).

Reservoir Quality Index is defined by

$$RQI=0.0314(k/\O_e)^{0.5} \quad .....(2)$$

Flow Zone Index is defined by

$FZI = RQI/\varnothing_z$ ...... (3)

where $\varnothing_z$ is normalized porosity

$\varnothing_z = \frac{\varnothing}{(1-\varnothing)}$.... (4)

Taking logarithm of both sides of Eq. 4, one gets

$\text{Log } RQI = \text{Log } FZI + \text{Log } \varnothing_z$ .... (5)

From equation 5, on a log-log plot of RQI vs. $\varnothing_z$, all samples with similar FZI values will lie on a straight line with a slope of one, and data samples with significantly different FZI values will lie on other, parallel, unit-slope lines. Samples that lie on the same straight line have similar pore throat attributes, and thereby, constitute a unique hydraulic flow unit. Each line is an HFU and the intercept of this line with $\varnothing_z$ = 1 is the mean FZI value for that HFU.
Now combining Eq 2 & 3 gives the permeability of each HFU which is given by

$K = 1014\,(FZI)^2 \varnothing\, \varnothing_z^2$ ....(6)

HFU Classification

In this work we applied histogram, probability plot and Hierarchical Clustering method for HU classification based on core data.

Histogram: Representation of FZI through histogram is an easiest method of finding the number of HUs. However often there is overlap of different distributions in histogram plot which makes this technique limited for HU classification. Figure 4 shows histogram of Log FZI and it is evident that HUclassification is difficult due to overlapping of different units.

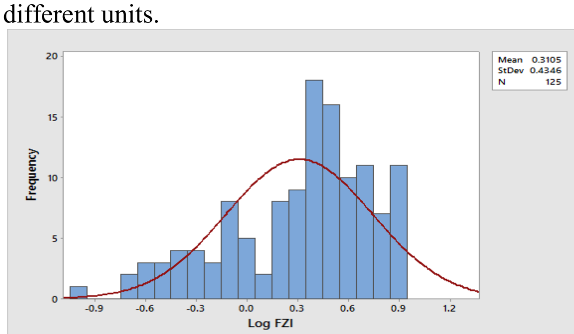


Figure 4: Histogram of Log FZI for 125 core plug data measurements.

Probability Plot: The probability plot is smoother than the histogram and hence the scatter in the data is reduced in this plot and the identification of clusters becomes easier. A normal distribution forms has a specially arranged coordinate system where each normal distribution forms a distinct straight line. Hence, the number of straight lines and the FZIlimiting boundary for each HU can be obtained from the probability plot of FZI. However superposition effects may shift or distort the straight lines to some degree. Figure 5 shows probability plot of FZI and seven HFU's were identified.

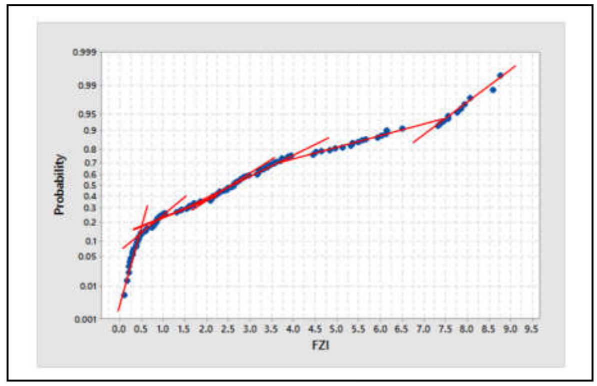


Figure 5: Normal Probability plot of FZI with division into 7 HUs

Irreducible water saturation is an intrinsic character of a reservoir unit. To understand the heterogeneity of the reservoir at capillary level, probability plot of S_{wi} of 41 core plug samples was done and same is given in Figure-6. It shows good reservoir unit with S_{wi} as low as 3% to poor reservoir with S_{wi} as high as 59%.

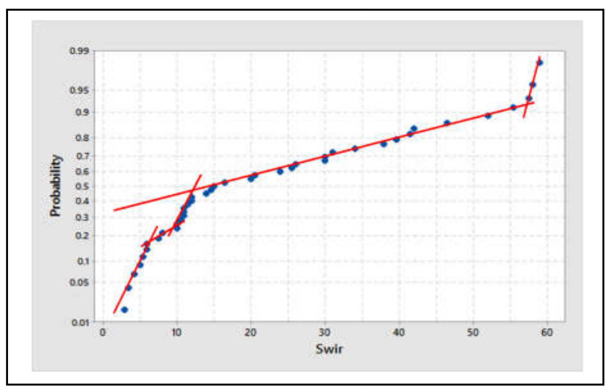


Figure 6: Normal Probability plot of Swi with division into 5 HUs

Hierarchical Clustering: Objective of Cluster analysis is to find natural groupings in data by grouping together objects that share similar characteristics (Bohling G. 2006). In this work Matlab was used to classify HU's based on Normalized porosity and RQI data as input using Ward's algorithm. The resulting dendogram is shown in Figure 7.

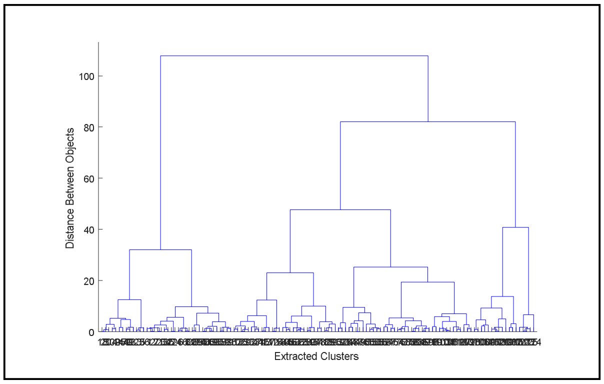


Figure 7:Dendogram of 125 core data set for Linch pay indicating nine possible classes.

Determining HU's for Linch Pay

Probability plot of FZI resulted into seven HU's for Linch Pays. It was followed by computation of RQI and $Ø_z$ from equation 2 and 4 using core data and a plot of RQI vs. $Ø_z$ was constructed (Figure-8). The unit slope lines were drawn for each HU through the data clusters according to the mean value of FZI calculated for each HU at the intercept $Ø_z$=1. The mean FZI values were then used to construct the porosity-permeability relationship with in each HU using Eq. 6 and same is plotted in Figure-9.

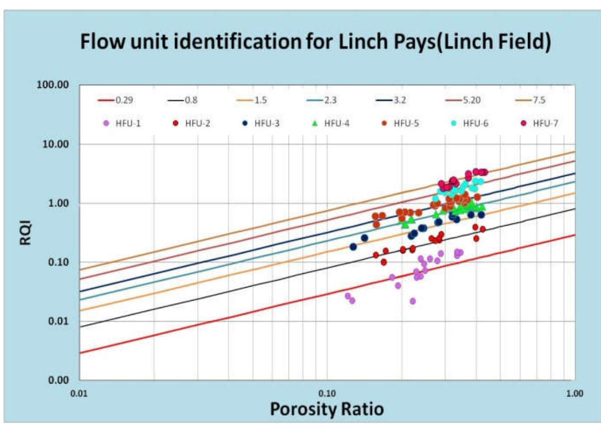


Figure 8: RQI vs. $Ø_z$ plot for all hydraulic units. The mean FZI values for each hydraulic unit are given by the intercept of the straight lines at $Ø_z$=1

A comparison of Figure-2 with Figure-10 indicate that identification of the HU's for Linch pay and subsequent grouping of the core porosity and permeability data has improved correlation significantly.

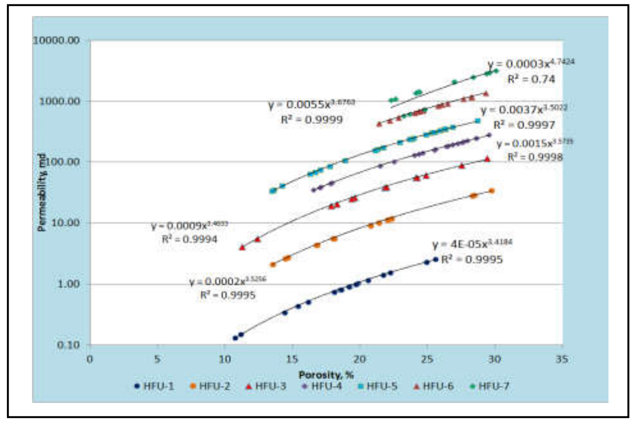


Figure-9:K_Predicted vs. Core_Porosityplot for all hydraulic units

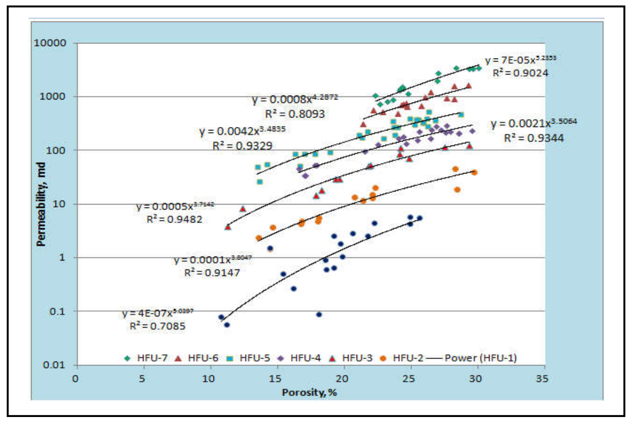


Figure-10: Core_Perm.vs. Core_Poro.plot for all the hydraulic units

Simple statistics of porosity, permeability and FZI (Table-2 to Table-4) indicate that classification method adopted in this work is able to describe 7 HU's those are individually homogeneous but different from others. Finally for each HU, permeability was calculated using Eq. 6 with mean FZI as shown in Figure 8. It was observed that FZI derived permeability is highly correlated with Core Permeability (Figure-11).

Table 2: Statistics of Core Porosity

HFU	N	Mean	Minimum	Q1	Median	Q3	Maximum	Range
1	18	18.96	10.76	15.97	19.20	21.86	25.59	14.83
2	15	20.49	13.53	16.77	20.78	22.33	29.73	16.20
3	13	20.97	11.26	18.07	21.81	24.54	29.38	18.12
4	22	24.171	16.570	20.605	25.545	27.598	29.580	13.010
5	27	22.131	13.460	17.760	23.730	25.920	28.690	15.230
6	15	25.347	21.410	24.020	24.710	27.660	29.290	7.880
7	15	25.681	22.320	23.660	24.420	28.370	30.090	7.770

Table 3: Statistics of Core Permeability

HFU	N	Mean	Minimum	Q1	Median	Q3	Maximum	Range
1	18	1.993	0.058	0.443	1.285	3.237	5.780	5.722
2	15	13.66	1.50	4.33	11.80	18.68	45.20	43.70
3	13	54.6	3.8	16.4	50.4	98.0	122.2	118.3
4	22	164.9	33.6	84.9	175.0	229.9	290.7	257.1
5	27	241.6	26.7	86.9	265.8	369.0	532.5	505.8
6	15	854.7	319.2	569.2	743.7	986.5	1637.0	1317.8
7	15	1923	737	1071	1440	3346	3499	2762

Table 4: Statistics of FZI Calculated

HFU	N	Mean	Minimum	Q1	Median	Q3	Maximum	Range
1	18	0.3447	0.1004	0.2397	0.3479	0.4522	0.6043	0.5039
2	15	0.8453	0.6003	0.7919	0.8549	0.9227	1.0393	0.4390
3	13	1.6452	1.3047	1.4922	1.6151	1.7771	2.0965	0.7918
4	22	2.4130	2.0997	2.2018	2.4407	2.6311	2.7513	0.6516
5	27	3.3452	2.7723	3.1713	3.3385	3.6041	3.9483	1.1761
6	15	5.187	4.451	4.653	5.324	5.581	6.028	1.577
7	15	7.413	6.127	6.512	7.563	7.935	8.762	2.635

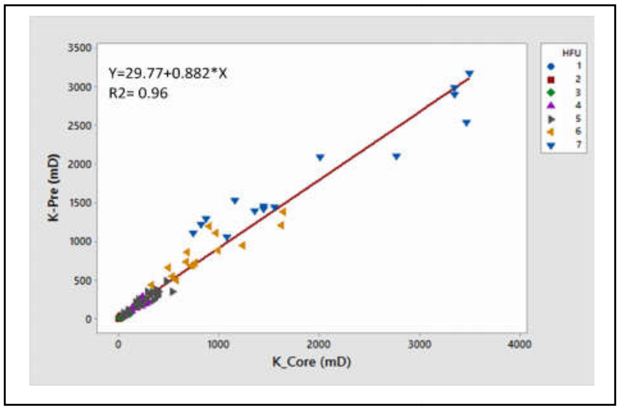


Figure-11: Correlation between Core Permeability and permeability calculated from FZI for HU's

Lithofacies of HFU's: Based on core data, lithological assemblages and petrophysical characteristics of hydraulic flow units have been studied. Broadly these flow units were classified into three groups. HFU's 5 to 7 are best flow units with good flow properties. These units are fine grained sandstone (quartzwacke) having thin and partially inclined both wavy and anastomosing laminae of argillaceous matter (Figure-12). The sandstone has more or less uniform grain size and occasional small burrows.Petrographically the sandstone is quartzwackehaving very fine to fine grained and angular monocrystalline quartz floating in argillaceous matrix. The grain boundaries are coated with fine siderite matter. The porosity is moderate and intergranular. The angularity of the grains and occasional presence of medium grained quartz is the characteristic feature of this rock unit (Das K.K et al. 2006).

HFU's 4 & 5 are also having good hydrocarbon flow properties too. Core study as shown in Figure 13 indicates that sandstone is quartzwacke which is mostly fine grained and exhibiting bimodality of very coarse, subrounded quartz grains. The quartz are monocrystaline and having floating to point contact. The porosity in general is moderate. The bimodality in grain size is attributed to burrowing activities (Das K.K et al. 2006).

HFU 3 is having moderate flow properties and core photograph of the same unit is given in Figure 14a. This unit is poorly sorted sandstone having randomly oriented pebble to granule sized clasts of siltyclaystone (Das K.K et. al. 2006).

Among seven flow units, HFU 1 and 2 are having poor flow properties. Core photograph of this unit is given in Figure 14b. This unit is dark grey to light grey in color which is composed of very fine to silt size quartz grains of sub angular to sub rounded nature and having moderate to poor sorting with poor visual porosity (Gupta A.K et al. 2012). Petrographically in these units, the laminated siltstone alternates with sideriticsilty shale laminae (Das K.K. et al. 2006).

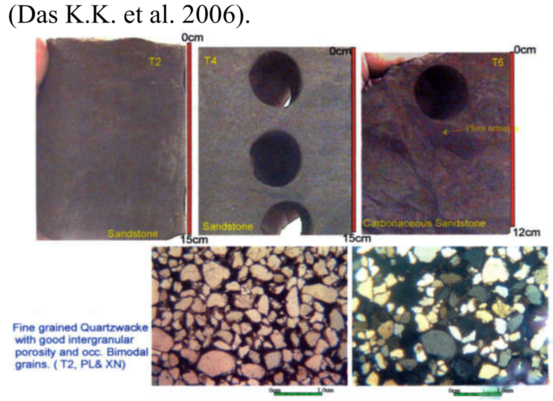
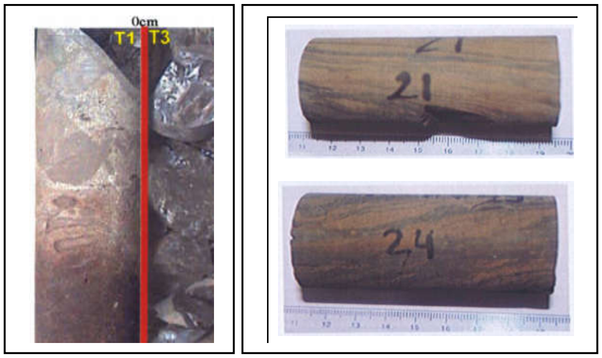


Figure-12: Core photographs and photomicrographs of HFU's 5 to 7 (Das K.K et al. 2006)

Figure-13: Core photographs of HFU's 4 & 5 (Das K.K et al. 2006)



(a) (b)

Figure-14: (a) Core photographs of HFU 3 (Das K.K et al. 2006) overlies the shale unit with a sharp contact.(b) Core photograph of HFU 1 & 2 (Gupta A.K et al. 2012)

Conclusions

The following conclusion could be made based on the results obtained from the study:

1. Linch Pay is heterogeneous in nature as observed by the moderate correlation between core porosity and permeability. This is also supported by the Winland plot and normal probability plot of S_{wi}.
2. Seven HFU's were identified based on FZI method for Linch Pay. HFU 4 to 7 are having good to very good reservoir flow properties. HFU 3 is having moderate flow properties due to poor sorting. HFU 1 & 2 are poor in nature as it is composed of laminated siltstone alternate with sideriticsilty shale laminae.
3. It was also observed that FZI method is very effective in permeability prediction as good correlation was obtained between core permeability and permeability calculated by FZI method.
4. HFU identification by FZI method is one of the important input in simulation work for prediction of reservoir behavior where each unit represent a type of rock with distinct petrophysical character that can be used to characterize the reservoir. Furthermore these HU's will be useful for permeability prediction and capillary based saturation height function modeling for each unit too.

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