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Research

Permeability prediction using hydraulic flow units and electrofacies analysis



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ABSTRACT

It is essential to characterize fluid flow in porous media to have a better understanding of petrophysical properties. Many approaches were developed to determine reservoir permeability among which the integrated analysis of hydraulic flow unit (HFU) and electrofacies (EF) is considered to be useful one. However, the application of HFU and EF analysis has not been totally understood with a limited data to develop correlation for less distance offset wells. In this study, an attempt was made to show the application of integrating HFU and EF for reliable estimation of permeability using core and wireline log data in one of the gas fields in Pakistan. The results obtained indicate that the integrated approach proposed in this study can be used, especially in less distance offset wells when a limited number of data are available for petrophysical characterization.

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1. Introduction

Comprehensive understanding of sedimentary, diagenetic and petrophysical characteristics of reservoirs plays a vital role for an accurate estimation of hydrocarbon reservoirs. Among the petrophysical characteristics, permeability is one of the key parameters to evaluate the fluid flow in porous media. Permeability can be estimated from well testing, core analysis and/or well logging based assessments, among which well logging and core data are often effectively utilized (Rafik and Kamel, 2017; Al-Ajmi and Holditch, 2000; Rezaee et al., 2007; Ismail et al., 2017).

Hydraulic flow units (HFUs) is referred to as lateral continuity of

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reservoir units with consistent geological properties controlling the behavior of fluid flow in pores media (Amaefule et al., 1993; Rezaee et al., 2007). Estimation of Permeability in heterogeneous reservoirs can be done based on different hydraulic flow units (HFUs) with a high accuracy (Torghabeh et al., 2014; Ismail et al., 2017) since HFUs are linked to the variation of lithology, petrophysical and flow attributes (Kochenov and Baturin, 2002). HFUs is a function of flow zone indicators (FZIs) which is measured from reservoir quality index (RQI) and normalized porosity (Abbaszadeh et al., 1996; Hearn et al., 1984). As a result, different methods have been used to evaluate FZIs and HFUs in different reservoirs (Abbaszadeh et al., 1996; Al-Ajmi and Holditch, 2000; Amaefule et al., 1993; Kazemzadeh et al., 2008; Prasad, 2003; Rezaee et al., 2007).

Electrofacies (EF) is referred to as a cluster of individual well logs with similar responses to certain reservoir characteristics (Lee and Datta-Gupta, 1999; Li et al., 2014). In this analysis, a clusters of well logs can provide a reflection of geological variations and petrophysical properties of reservoirs (Ye and Rabiller, 2000; Rezaee et al., 2007).

There have been many studies carried out in the past few years

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Fig. 1. Location map of the study area (Ismail et al., 2017).

where attempts were made to determine permeability using HFU-, FZI- and EF-based analysis. For instance, Kadkhodaie-Ilkhchi et al. (2013) utilized porosity and permeability data for reservoir electrofacies (EF) prediction using clustering approach in two individual sedimentary and petrophysical aspects. In addition, hydraulic flow units (HFUs) were introduced in order to find a good connection between EFs and production zones within sandy packages (Kadkhodaie-Ilkhchi et al., 2013). Abed (2014) predicted permeability of rock mass from core and well log-data based on hydraulic flow units in link k-means and flow zone indicator (Abed, 2014). The correlations were found by a suitable approach to estimate permeability in un-cored wells at the flow unit scale. El Sharawy and Gaafar (2016) adopted the statistical reservoir zonation technique including cluster analysis to divide the zones into electrofacies depending on permeability, porosity, bulk density, acoustic impedance and interval transit time for variation in separation depth and zones continuity (El Sharawy and Gaafar, 2016). Min et al. (2016) carried out simulation study for porosity-permeability relationships under different mineral distributions and reactive transport conditions and found that it is extremely challenging to propose general relationships due to the complicated interactions between reactive transport and mineralogical heterogeneity (Min



Fig. 2. Stratigraphy and subdivision of Lower Goru Formation (Ahmad et al., 2004).



Fig. 3. Flow chart of methodology developed for the purpose of this study.



Fig. 4. Multi well correlation of C-Sand in the Study Area (Ismail et al., 2017).

et al., 2016). Tang and McDonough (2016) proposed an analytical permeability model for incompressible fluid flow based on a nonequilibrium thermodynamic stability theory to maximize the production rate to achieve a stable system (Tang and McDonough, 2016). In another study, Rafik and Kamel (2017) predicted permeability using non-parametric regression and multivariate statistical analysis (Rafik and Kamel, 2017). Iravani et al. (2017) developed an equation using seismic attribute to predict FZI throughout the Table 1

Top and bottom of C-Sand.

Well Name	Horizon	Top (m)	Bottom (m)	Thickness (m)
Sawan-07	C-Sand	3266	3365	99
Sawan-09	C-Sand	3269	3392	123
Sawan-01	C-Sand	3253	3395	142
Sawan-08	C-Sand	3267	3365	98
Sawan-02	C-Sand	3260	3367	107
Sawan-3B	C-Sand	3396	3510	114



Fig. 5. Bivariate porosity-permeability regression.

reservoir. The optimum number of Hydraulic Flow Units (HFU) was determined by analyzing the break point in the plot of cumulative frequency of FZI for wells (Iravani et al., 2017). Considering these issues, it would be challenging to develop a general relationship for the determination of permeability. The aim of this study is to utilize hydraulic flow unit and electrofacies (cluster analysis) concept with limited data to estimate the permeability of one of the Pakistani gas fields.

2. Methodology

The Sawan Gas Field in Pakistan was chosen for the purpose of this study which is located in the Badin basin (see Fig. 1) with 1534 billion cubic feet of recoverable gas reserves and hosts 12 production wells. This field has been used previously in few studies on sand management (McPhee and Enzendorfer, 2004), depositional environmental related analysis (Berger et al., 2009), and permeability estimation (Ismail et al., 2017). The lithology of the field ranges from sublith-arenites to lithic arenites sand with a high mixture of volcanic fragments (McPhee and Enzendorfer, 2004). The major change in the facies was observed during drilling in the Badin area where productive sand shale facies. Thus zone of facies change was later identified as a hydrocarbon-bearing zone.

The Cretaceous Lower Goru formation is mainly categorized into

sands layers of A, B, C and D which are separated by Turk shales as shown in Fig. 2.

Research methodology adopted (See Fig. 3) in this study involves utilizing core and well logging data to develop poro-perm relationship by identifying horizons, hydraulic flow unit and electrofacies. The core measured permeability is used to verify the predicted permeability coming from the developed model.

In this methodology, the multiwell correlation for horizons of six wells was obtained using mud logs, geophysical logs and available literature. Having highest values of routine core analysis data as compared to other wells, Sawan-07 well was selected and evaluated along with well logging data to identify hydraulic flow units and electrofacies contribution in improvement of porositypermeability relationship in C-Sand. Sonic and deep resistivity logs of Sawan-02 and Sawan-08 wells were not used because of evident bore-hole effects. Gamma ray (GR), Sonic (DT), Deep resistivity (LLD), Density (RHOB) and Neutron Log (NPHI) were the main logs used in this study together with the mud log information present for all wells. Consequently, different intervals were distributed into subunits based on the flow zone indicator values. To do this, C-Sand layer was divided into hydraulic flow units based on the reservoir quality index (RQI) and flow zone indicator calculated from core data of Sawan-07 well. Reservoir quality can be calculated using the following equations (Abbaszadeh et al., 1996; Amaefule et al., 1993):

$$R_{qi} = 0.0314 \sqrt{\frac{k}{\phi_e}} \tag{1}$$

$$\phi_z = \frac{\phi_e}{(1 - \phi_e)} \tag{2}$$

$$R_{qi} = \phi_z \times F_{zi} \tag{3}$$

$$\log(R_{qi}) = \log(\phi_z) + \log(F_{zi}) \tag{4}$$

where R_{qi} is the reservoir quality index (RQI), ϕ_e is the core porosity, k is the core permeability, ϕ_z is the normalized porosity and F_{zi} (µm) is the flow zone indicator. The RQI and normalized porosity data points align themselves in a straight line on log-log plot representing a specific set of flow zone indicator values. Mean flow zone indicator is the intercept of the line at $\phi_z = 1$ (Deghirmandjian, 2001). Bivariate regression analysis was done for each hydraulic flow unit of C-Sand interval in which each has specific flow zone indicator range and poro-perm. Flow zone indicator values were used to estimate permeability of Sawan-7 well. Histogram analysis was used to determine the mean flow zone indicator. Depending on the availability of data, electrofacies analysis was done on Sawan-01, Sawan-07, Sawan-09 and Saawan-3B wells.

3. Results and discussion

The C-Sand interval/reflector was picked using the well log signature matching the technique proposed by Abbas et al. (2015) in Sawan-02 well and \ correlated laterally in offset wells. The multiwell correlation for horizons of six wells was generated using mud logs, geophysical logs and available literature where it was found that C-Sand interval is dipping downward moving from Sawan-01 to Sawan-3B. The gamma ray signature shows that upper zone of the C-Sand has relatively less amount of clay compared to the lower one as displayed in Fig. 4. Mud log of each well had top and bottom depth for Lower Goru formation as listed in Table 1. It was also reported that the

FΖ



Fig. 6. a, Core data clustering into hydraulic flow units (left); b, histogram of low zone indicator (FZI) for each hydraulic flow unit (right).



Fig. 7. Bivariate regression analysis for hydraulic flow units in Sawan-07 Well.

Table 2The results of bivariate regression analysis for hydraulic flow units.

$\begin{array}{ccc} \text{HFU1} & Log(Core_K) = 1.2 + \\ \text{HFU2} & Log(Core_K) = 0.5 + \\ \text{HFU3} & Log(Core_K) = -0.3 \\ \text{HFU4} & Log(Core_K) = -0.9 \\ \text{HFU4} & Log(Core_K$	$3.3 \times Core_PHI$ $R^2 = 0.83$ $3.6 \times Core_PHI$ $R^2 = 0.87$ $5 + 10.83 \times Core_PHI$ $R^2 = 0.94$ $+ 11.8 \times Core_PHI$ $R^2 = 0.93$ $+ 12.4 \times Core_PHI$ $R^2 = 0.93$



Fig. 8. Measured permeability from routine core analysis and estimated permeability by hydraulic flow unit approach.

sandstone of the Sawan field has shallow-marine setting with a medium to coarse grain mineralogy. A huge amount of volcanic fragments are present in the C-Sand interval of Lower Goru Formation compared to A and B Sand intervals (Berger et al., 2009).

For the reservoir interval prior to hydraulic flow units/electrofacies analysis, the regression analysis was carried out for Sawan-07 well based on core data and a correlation of 80% was achieved (Eq. (5)) as shown in Fig. 5. In such data set, there will be data points corresponding to all ranges of reservoir geological properties. The reason for the high regression coefficient for the interval of C-Sand can be attributed to the absence of HFU and variation in the heterogeneity of different geologic units.

$$Log(Core_K) = -2.6 + 21.3 \times Core_PHIR^2 = 0.79$$
 (5)

Where Core_K and Core_PHI are the measured permeability and porosity from the core analysis respectively.



Fig. 9. Subdivision of HFU5 into HFU5A and HFU5B.

Reservoir quality index, flow zone indicator and normalized porosity were determined from the core data of Sawan-07 well. Log-log plot of RQI and normalized porosity were used to separate the reservoir interval into definite geological units by following an approach proposed (Deghirmandjian, 2001). A total number of five units were found with specific class of petrophysical properties. The range of FZI was determined for each hydraulic flow unit by cross plotting the data points of reservoir quality index (RQI) and normalized porosity (ϕ_z), providing the distinct flow units straight line. With reference to the secondary vertical axis, the FZI values range from 7 to 10 µm for HFU1, 3–6 µm for HFU2, 2–3 µm for HFU3, 1–2µm for HFU2 and 0–1 µm for HFU1, as shown in Fig. 6a.

In Fig. 6a, each line only gives one FZI value, that is $FZI_{mean.}$ Histograms were used to determine the mean flow zone indicator used to estimate permeability in Sawan-07 for the identified flow units (see Fig. 6b). The developed porosity and permeability model expressed in Eq. (6) was used for each hydraulic flow.

$$k = 1014 \times (FZI_{mean})^2 \times \frac{\phi_e^3}{\left(1 - \phi_e\right)^2} \tag{6}$$

C-Sand was divided into 5 units and bivariate regression analysis was done between permeability and porosity. Regression coefficients for HFU1, HFU2, HFU3, HFU4 and HFU5 were then obtained as 83%, 87%, 94%, 93% and 49% respectively (see Fig. 7). The results of the regression analysis for the hydraulic flow units are given in Table 2.

The similarity between the slope of the linear fitted line between porosity and permeability of hydraulic flow units showed the correspondence of geological conditions. The above-mentioned slope would have been the same as that of particular hydraulic flow unit laterally in offset wells if depositional environments had been the same from well to well.

It is also clear from depth plot (see Fig. 8) of measured permeability from routine core analysis and estimated permeability from hydraulic flow unit that every precise range of permeability corresponds to a specific range of flow zone indicator, reservoir quality indicator and normalized porosity values for reservoir rock.

The data points in the HFU5 are scattered as evident in Fig. 7 which interpreted that low value of regression coefficient of HFU5 in HFU5 has petrophysical properties of mixed types. The flow zone indicator for HFU5 ranges from 0 to 1 µm. Coefficient of regression is very low (49%) in HFU-5 as compared to that of other hydraulic flow units. To improve the interrelation of porosity and permeability, HFU-5 was divided in to two more hydraulic flow units as HFU5A and HFU5B and high regression coefficients for the data after division signified the subdivision of HFU (see Fig. 9). Dividing the method will give more space for selection of optimum data points for the generation of regression relationships. Further subdivision will never propagate to next one or two steps because almost all data will be sorted into these two steps if any very low data point is found in lower subdivision steps, regression relationships should not be developed for these hydraulic flow units. The increment in the coefficient of regression for HFU5 from 49% to 86% and 60% signified the relation of pore throat size distribution with poro-perm relationship. Flow zone indicator values range from 0 to 0.5 µm and 0.5-1 µm for HFUA and HFUB respectively.

To get high resolution subdivision of C-Sand, rock typing algorithm k-mean square was used which has used well log response to divide the formation in discrete units termed as electrofacies. Electrofacies analysis is a technique which is based on clustering of data corresponding to distinct lithological properties using well log response. Electrofacies is carried out based on k-mean clustering approach (Lin et al., 2014; Li and Wang, 2014) that is one of the widely used clustering techniques in handling large data sets.

To compare the HFU and EF ability for estimating the regression coefficient of porosity-permeability relationship, the well log response was used to divide to C-Sand into units. Fig. 10 shows different cross plots of well log responses identifying different zones using the electrofacies technique on four well log data. The well log responses of each well used in the study are shown using different colors. This plot is generated using the values of flow zone indicator for the study zone. A proper cutoff of each hydraulic flow unit with specific color was applied on the FZI values. The cutoff and the color code show the distribution of

Multi-Curve Crossplot







Fig. 11. Subdivision of C-Sand interval into distinct zones using electrofacies analysis.

FZI in each hydraulic flow units. The main purpose of this histogram is to calculate the mean value of FZI in each HFU and analyze the distribution of the frequency of FZI in the identified units.

Depending on availability of data, electrofacies analysis was done on Sawan-01, Sawan-07, Sawan-09 and Saawan-3B wells. The suggested optimum division of the study depth fall into four zones which were correlated laterally in each well. The separated zones are Z-1, Z-2, Z-3 and Z-4 as shown in Fig. 11. Gamma ray log shows that Z-1, Z-2 and Z-3 have clean sand lithology while Z-4 has high clay content. Fig. 12 shows that bivariate regression of each zone for Sawan-07 well. It was found that regression coefficients for Z-1, Z-2 and Z-3 are 89%, 79% and 91% respectively while no suitable data are available in Z-4 to carry on regression analysis. The results of bivariate regression in Sawan-07 well are given in Table 3.

The results of regression analysis in Z-3 are somehow doubtful due to shortage of data. The subdivided zones, Z-1 and Z-2 by electrofacies of C-Sand, have high thickness in Sawan-01 and Sawan-07 wells dipping towards Sawan-3B. The developed poro-perm regression analysis was applied on Sawan-02 and Sawan-3B wells. The estimated permeability from regression results has a 97% correlation with measured permeability of Sawan-02 well (see Fig. 13). This shows that porositypermeability equation generated for Sawan-07 well can be used in the offset wells. On application of the same equation on Sawan-3B well, the regression coefficient between estimated and measured permeability of Sawan-3B well is obtained 70%. Sawan-3B well is almost two-fold away from Sawan-07 well as compared to Sawan-02 well. This shows the limitation of conventional bivariate regression analysis, where accuracy of estimation decreases as applying the porosity-permeability equation to greater distance from source of development.

Very limited data on core are available for Sawan-3B well to check the reliability of bivariate regression-based equation for potential part of C-Sand in Sawan Field as compared to Sawan-02 well. The developed relationships for zones from electrofacies analysis were applied on zones of offset wells. A zone in Sawan 3B well was selected rather than Sawan-02 due to available data for electrofacies analysis. It was found that only routine analysis of 2 core samples was made in Z-1 of Sawan-3B well which may lead to doubtful results (see Fig. 13). The bivariate regression analysis of Z-1 of the Sawan-07 well was applied to Z-1 of Sawan-3B well which showed surprisingly 100 percent regression coefficient as given in Fig. 14. The data is limited in Z-1 of Sawan-3B to support the mentioned results.

4. Conclusion

The integrated analysis of hydraulic flow unit (HFU) and electrofacies (EF) techniques is found useful with limited data to develop the poro-perm relationship to predict the permeability in un-cored wells, especially less distance offset wells. It was found that for precise identification of hydraulic flow units, data should be sorted in terms of narrow range of flow zone indicator for a better estimation of permeability in terms of porosity.

In this study, an attempt has been made to estimate reliable permeability value in one of the gas fields in Pakistan utilizing available limited data (core and we HFU and EF. The results indicated that this integrated approach is applicable with limited data, serving to improve the regression coefficients and accuracy of poro-perm relationship. The regression coefficient of poroperm relationship is in turn improved by tracing precise and narrow units of the reservoir rock using hydraulic flow unit (HFU) and electrofacies (EF) techniques. In addition, the hydraulic flow unit and electrofacies analysis functions to improve



Fig. 12. Bivariate regression analysis of electrofacies zonation.

Table 3

The results of bivariate regression in Sawan-07 well.

Zones	Correlation	Regression Parameter
Zone 1	$Log(Core_K) = -3.8 + 27.4 \times Core_PHI$	$R^2 = 0.89$
Zone 2	$Log(Core_K) = -2.5 + 21.0 \times Core_PHI$	$R^2 = 0.78$
Zone 3	$Log(Core_K) = -3.4 + 22.6 \times Core_PHI$	$R^2 = 0.90$



the regression coefficients of porosity and permeability equation, almost up to 14% and 11% respectively. The developed poro-perm relationship for C-Sand interval in Sawan-07 well is better applied to Sawan-02 well as compared to Sawan-03 well, which may be due to lateral heterogeneities.



Fig. 13. Estimated permeability versus measured permeability of Sawan-02 (left) and Sawan-3B (right).



Fig. 14. Estimated permeability versus measured permeability in Z-1 of Sawan-3B.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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