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Methods for Determination of Hydraulic Flow Units Using Petrophysical Parameters (Case Study from South Pars Gas Field, Iran)

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***Abstract* — The purpose of this study is to compare methods for determining hydraulic flow units and to evaluate the quality of the reservoir as well. This study relates to the two reservoir zones K1 and K2, in the Kangan Formation in well SP-a with the Triassic age. In this research, well logging data and petro-physical data, have been used in Geolog and Excel softwares. Various methods have been used to determine hydraulic flow units. Among the existing methods, the Lorenz method and FZI cumulative histogram were preferred to the other methods. By applying methods on the data obtained from Kangan reservoir six and eight flow units were identified respectively for the two reservoir zones of K1and K2. This investigation showed that in the (SP_a) well at depth interval between 2860-3010 meters total of Fourteen hydraulic flow units have been selected. Based on our calculations and interpretation of well data, reservoir zones of K2 have higher reservoir quality than K1. The study of gas production from this well, shows that determination of hydraulic flow units in the reservoir zones of this well, can help to prevent the production of water in the beneficiary zones.**

***Keywords* — Hydraulic flow unit; quality of reservoir; Kangan Formation; South Pars gas Field.**

I. INTRODUCTION

Several types of porosity-permeability transforms are available to determine permeability from well log-derived porosity in uncored oil and gas wells. Typically these transforms put emphasis on lithology or facies during reservoir characterization. In addition, several pore system dependent techniques are also published. Shenawi et al. (2009) have described commonly used porosity-permeability transform types, such as: i) transforms by facies, ii) by Winland technique, iii) by pore geometry, and iv) by geologic zones. Transforms by hydraulic unit approach provide way better results than those typical transforms. Rock typing by hydraulic units can be defined as units of rock that have unique porosity-permeability relationship, capillary pressure profiles and relative permeability curves. It has many applications in reservoir characterization and simulation studies. Once the rock typing is done properly, it can lead to a reliable estimation of the permeability in the uncored wells, accurate generation of initial water saturation profiles and consequently, reliable reservoir simulation studies (Davies et al., 1996; Guo et al., 2005; Shenawi et al., 2007).

II. CASE STUDY

A. GEOLOGICAL SETTING AND STRATIGRAPHY

South Pars gas field is located in the Central Persian Gulf at the NE margin of the Arabian Plate (Fig. 1). This area is underlain by the NNE-SSW trending Qatar – South Fars Arch which is bounded by the Zagros foldand-thrust belt to the NNE (Alsharhan and Nairn, 1997; Konyuhov and Maleki, 2006; Bashari, 2005; Perotti *et al.*, 2011). The Arch was a positive structure for much of the Palaeozoic but gradually subsided in the Jurassic (Saint-Marc, 1978; Esrafili-Dizaji and Rahimpour-Bonab, 2013). Due to Hercynian upwarping in the Late Palaeozoic, the sedimentary cover thins over the Arch, and over similar structures elsewhere in the Arabian Plate (Alsharhan and Nairn, 2003). In the northern Arabian Plate, the Permian-Triassic succession is dominated by a thick shallow-marine carbonate-evaporate succession developed on the northern passive margin of Gondwana (Edgell, 1996; Pillevuit, 1993; Sharland *et al.*, 2001) which in general shows a stratiform or “layer cake” geometry (Insalaco *et al.*, 2006; Alsharhan *et al.*, 2006; Ehrenberg *et al.*, 2007; Koehrer *et al.*, 2010, 2012; Zeller *et al.*, 2011). In Iran, this succession is referred to as the Dalan and Kangan Formations (Fig. 2) which are stratigraphic equivalents of the Khuff Formation in areas to the south (Alsharhan, 2006). The Late Permian Dalan Formation is divided into limestone and dolostone members separated by the Nar evaporate member (Edgell, 1977; Fig. 2B). The Dalan is overlain by the Early Triassic Kangan Formation which passes up into the Dashtak Formation (Szabo and Kheradpir, 1978).

The Kangan-Dalan succession can be divided into five reservoir units, k1-k5 (Fig. 2B), based on lithological properties (Alsharhan and Nairn, 2003). In this study, we focus on the K1and K2 reservoir units in the Kangan Formation.

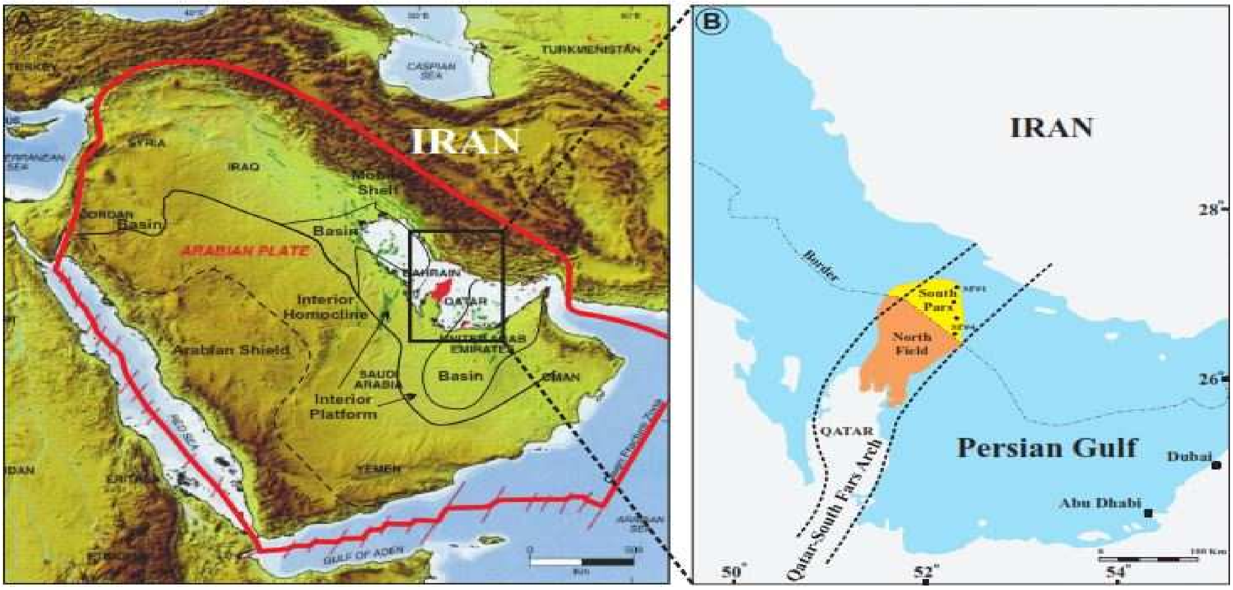

FIGURE.1. (A) REGIONAL MAP OF THE ARABIAN PLATE WITH STRUCTURAL SUBDIVISIONS (COMPILED FROM POWERS ET AL., 1966; SHARLAND ET AL., 2001; KHALIFA, 2005). (B) LOCATION OF THE SOUTH PARS GAS FIELD, THE STUDIED WELL, AND THE QATAR – NORTH DOM

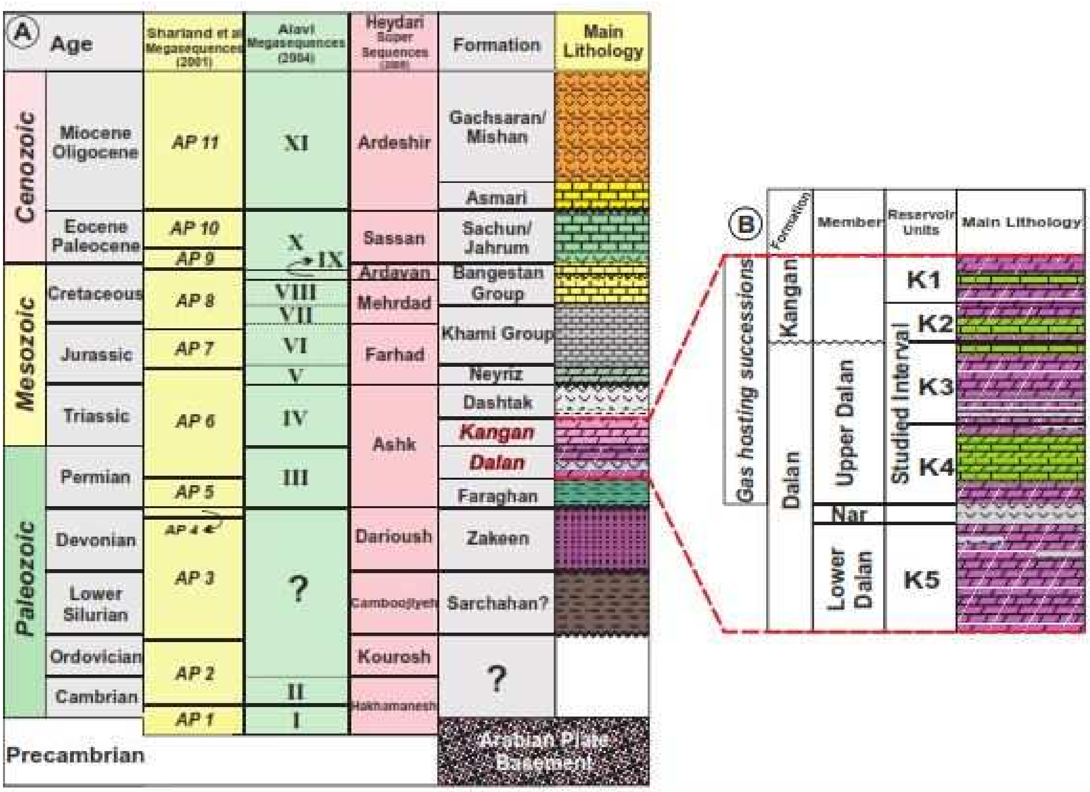

FIGURE. 2. (A) STRATIGRAPHIC COLUMNS FOR THE CENTRAL PERSIAN GULF (SOUTH PARS GAS FIELD) AND THE STRATIGRAPHY OF THE PERMO-TRIASSIC. (B) RESERVOIR ZONES AT THE SOUTH PARS FIELD SHOWING THE STUDIED INTERVAL (AFTER RAHIMPOUR-BONAB ET AL., 2014).

B. DETERMINATION METHODS

In the first step, the permeability is needed because there is no core data from the well. So we used the results obtained from well log analysis of the well SP_A in Geolog software based on the effective porosity and irreducible water saturation and permeability calculate from Wyllie and Rose equation using the excel software . Wyllie and Rose investigated the effect of irreducible water saturation and porosity on the permeability, and developed the following empirical relation.

$$K = \left(\frac{a_{wr}\varphi^3}{S_{wi}}\right)^2 \qquad (1)$$

Where a_{wr} is a constant depending on the hydrocarbon density. For the medium gravity oil $a_{wr} = 250$ and for dry gas $a_{wr} = 79$. K is in mD, *and* φ, S_{wi} are in fractions. Since, the study area is gas reservoir, a_{wr} is selected to be 79, then the output data used for determination of HFU by various methods. Comparison methods of HFU are only applied by some operators for the South Pars gas field (Figure-3).

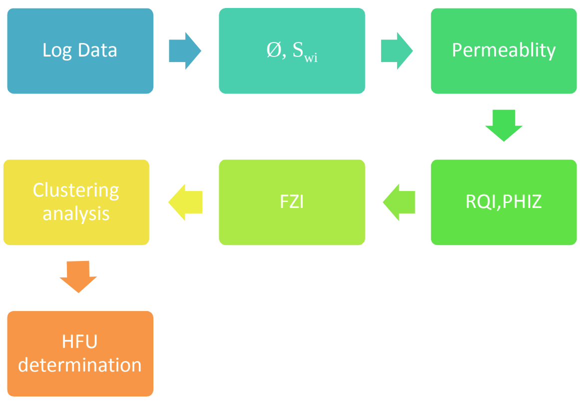

FIGURE.3. HFU DETERMINATION PROCESS IN THIS STUDY

C. Classification of hydraulic flow units

Flow units based on petrophysical characteristics can be defined using statistical techniques. Tiab and Donaldson (2004) proposed a method to identify flow units based on the modified Koseny–Carman equation and the concept of mean hydraulic radius, where each hydraulic flow unit is defined by a specific value of the flow zone indicator (FZI). The FZI is determined from log analysis (porosity and permeability) and calculated data using the rock quality index (RQI) and the normalized porosity (PHIZ) (Amaefule *et al.*, 1993; Ghiasi-Freez *et al.*, 2012). The RQI can be calculated using the following equation:

$$\mathrm{RQI} = 0.0314\sqrt{\frac{k}{\Phi e}} \tag{2}$$

The normalized porosity Φz is defined as:

$$\Phi z = \frac{\Phi e}{1-\Phi e} \tag{3}$$

The Flow Zone Indicator (*FZI*) is defined as:

$$\mathrm{FZI} = \frac{\mathrm{RQI}}{\Phi z} \tag{4}$$

Ideally, on a log-log plot, the RQI versus PHIZ, samples with similar FZI values will lie on a straight line with a slope of one; samples with significantly different FZI values will lie on other parallel line (unit-slope lines). Samples that lie on the same straight line have similar pore throat attributes, and there by constitute a unique hydraulic flow unit (Fig.4). Accordingly, each line represents an individual HFU (hydraulic flow unit) with similar FZI values. The basis of HFU classification is to identify groups of data that form unit-slope straight lines on a log-log plot of RQI versus PHIZ (Al-Ajmi and Holditch, 2000; Kadkhodaie-Ilkhchi and Amini, 2009). In heterogeneous reservoirs, identifying the straight lines through dispersed data and selecting the boundaries of flow units can be an uncertain and inaccurate process. To overcome this problem, clustering methods can be used to control the boundaries of the flow units. Different hydraulic flow units can be identified based on FZI values. In general, FZI dispersal is a function of data distribution around the mean FZI. Decomposition of the overall FZI distribution into its constituent components is required to determine the flow units. Cluster analysis permits such a decomposition process. The purpose of cluster analysis is to categorize a dataset into groups which are internally homogeneous but which are externally isolated on the basis of a measure of similarity or dissimilarity (Abbaszadeh *et al.*, 1996).

In this study, graphical clustering methods such as histograms and normal probability plot analyses were used to determine the number of hydraulic flow units and also the boundaries between them. Histograms of Log FZI and log-log plots of RQI versus PHIZ are the simplest analytical methods for determining the optimal number of hydraulic flow units which controlling fluid flow in reservoir rock.

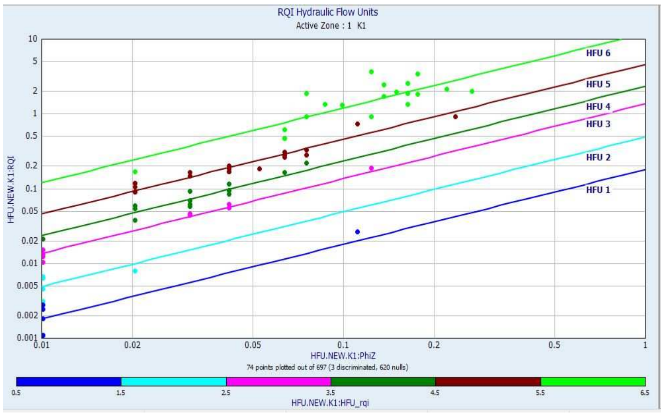

Figure 4. Plot Of Rock Quality Index (RQI) Versus Normalized Porosity (Phiz) Showing The Results Of Ascendant Hierarchical Clustering For Classification Of Well Log Data From The Kangan (K1) Formation In Training Well SP_A (Depth 2860-2966 m) At South Pars Gas Field. The Plot Shows That Six Flow Units Can Be Identified As Indicated By The Different Lines.

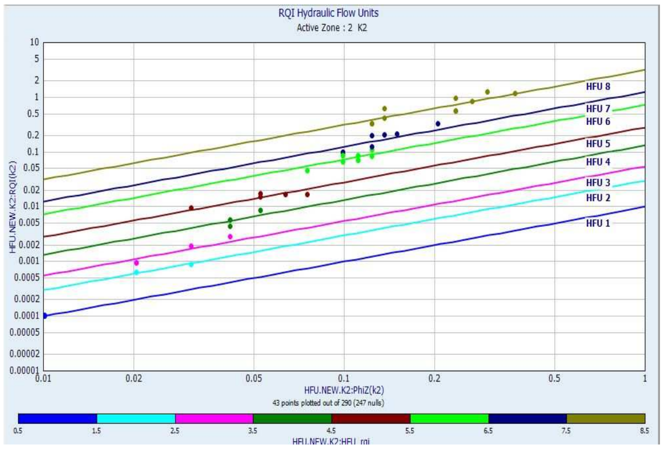

Figure 5. Plot of rock quality index (RQI) versus Normalized porosity (phiz) showing the results of ascendant hierarchical clustering for classification of Well log data from the Kangan (K2) Formation in training well SP_A (depth 2966-3010 m) at South Pars gas field. The plot shows that eight flow units can be identified as indicated by the different lines.

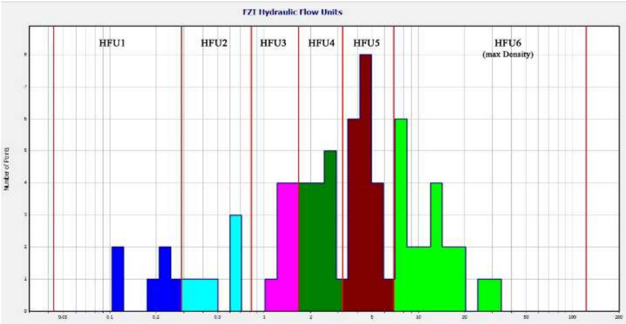

FIGURE.6. HISTOGRAM OF FZI DATA FOR THE KANGAN (K1) FORMATION IN TRAINING WELL SP_A (DEPTH 2860-2966 M) AT SOUTH PARS GAS FIELD, THE HISTOGRAM SHOWS THAT SIX FLOW UNITS CAN BE IDENTIFIED AS INDICATED BY THE RED LINES.

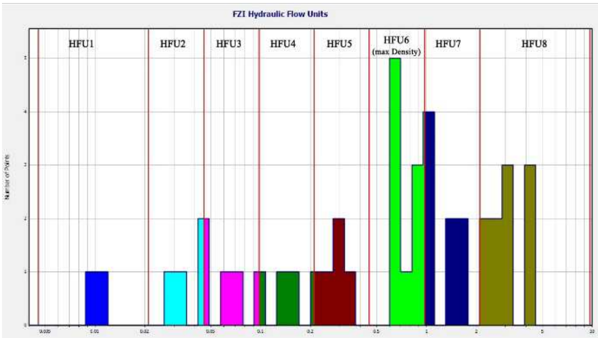

FIGURE.7. HISTOGRAM OF FZI DATA FOR THE KANGAN (K2) FORMATION IN TRAINING WELL SP_A (DEPTH 22966-3010 M) AT SOUTH PARS GAS FIELD, THE HISTOGRAM SHOWS THAT EIGHT FLOW UNITS CAN BE IDENTIFIED AS INDICATED BY THE RED LINES.

Finally, the advanced Lorenz plot is created from the porosity and permeability data for the selected data sets. The data is reverse sorting using the FZI value associated with each Phi / Perm pair. The sorted data is then linearly accumulated and normalized to a give a maximum value of 1.0. The cumulated porosity (‘Cumulative Storage Capacity’) is plotted of the X axis. The cumulative permeability (‘Cumulative Flow Capacity’) is plotted on the Y axis. The Z axis is the FZI and is plotted as a color scale. The Lorenz plot can be used for picking the flow unit boundaries at inflection points on the Lorenz curve (Gunter et al, 1997). Also base on space between curve B and straight line A we have heterogeneity in reservoir, as much as increase this space the degree of heterogeneity is going up and invers as much as decrease this space the degree of heterogeneity is going down, as a result when this space is zero (cure B matches on straight line A), we don’t have heterogeneity in reservoir and the other hand we can say the reservoir is Homogenous (Ghassem Alaskari, M.K., 2012).

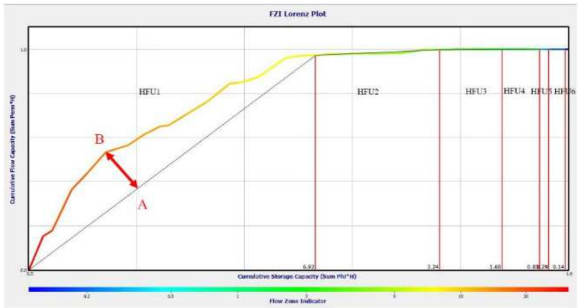

FIGURE 8. PLOT OF NORMALIZED CUMULATIVE STORAGE CAPACITY ($\sum_1^n \varphi h$) VERSUS NORMALIZED CUMULATIVE FLOW CAPACITY($\sum_1^n kh$) SHOWING THE RESULTS ADVANCED LORENZ PLOT FOR CLASSIFICATION OF WELL LOG DATA FROM THE KANGAN (K1) FORMATION IN TRAINING WELL SP_A (DEPTH 2860-2966 M) AT SOUTH PARS GAS FIELD. THE PLOT SHOWS THAT SIX FLOW UNITS CAN BE IDENTIFIED AS INDICATED BY THE RED LINES.

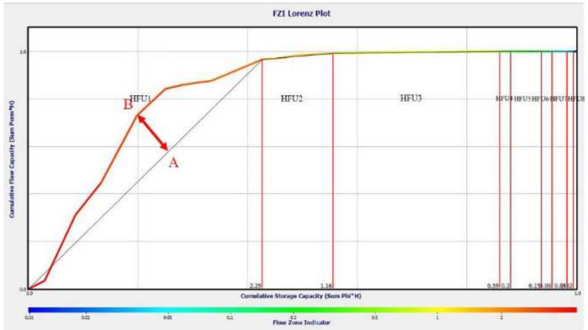

FIGURE 9. PLOT OF NORMALIZED CUMULATIVE STORAGE CAPACITY ($\sum_1^n \varphi h$) VERSUS NORMALIZED CUMULATIVE FLOW CAPACITY ($\sum_1^n kh$) SHOWING THE RESULTS ADVANCED LORENZ PLOT FOR CLASSIFICATION OF WELL LOG DATA FROM THE KANGAN (K2) FORMATION IN TRAINING WELL SP_A (DEPTH 2966-3010 M) AT SOUTH PARS GAS FIELD. THE PLOT SHOWS THAT EIGHT FLOW UNITS CAN BE IDENTIFIED AS INDICATED BY THE RED LINES.

Based on Figures (8 and 9) the two reservoir zones discussed above have some degree of heterogeneity but in K1 this heterogeneity lowest than the K2 zone.

D. *WINLAND R35 METHOD:*

The selection of the flow unit using the Winland method calculated from the following equation (Martin et al., 1997)

WinR35 = A Log(0.732 + 0.588 Log(K) – 0.864 Log(ϕ))

where is ϕ in percent and Permeability is in mD.

The Winland equation was created by Dale Winland of Amoco. It is an empirical equation where R35 is the pore aperture radius corresponding to the 35th percentile of mercury saturation in a mercury porosity metry test, K air is the uncorrected air permeability(in md) and ϕ core is porosity in %. The equation was originally defined from mercury porosity metry measurements on some 300 samples from the Spindle Field in Colorado. Winland correlated porosity and permeability to pore throat radii corresponding to different mercury saturations and found that the 35th percentile gave the best correlation. The 35th percentile was taken to approximate the modal class of pore throat size where the pore network becomes interconnected forming a continuous fluid path through the sample. More accurately, the above is only true at the pore throat size corresponding to the point of inflexion of the pore throat size versus mercury saturation plot. Winland used an R35 value of 0.5µm as the definition of net pay for the Spindle Field due to evidence he had seen of dry wells having an R35 of <0.5µm and producing wells with R35>0.5µm. The value of 0.5µm has since been used in other reservoirs to define pay.The WinR35 data is clustered into 25 nodes using K mean clustering. Then the cluster nodes are re-clustered into the number of selected flow units using Hierarchical clustering.

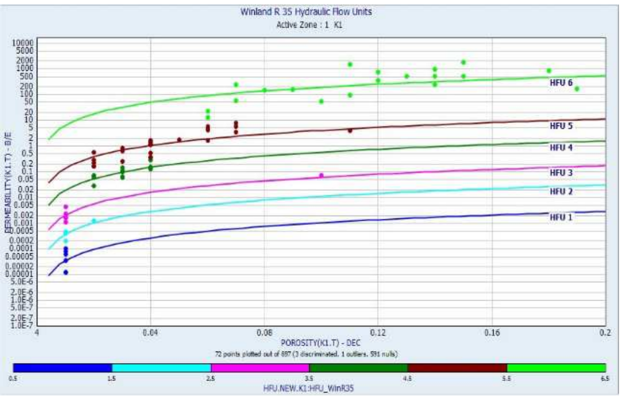

FIGURE. 11. PLOT OF WINLAND R35 SHOWING THE RESULTS OF ASCENDANT HIERARCHICAL CLUSTERING FOR CLASSIFICATION OF WELL LOG DATA FROM THE KANGAN (K1) FORMATION IN TRAINING WELL SP_A (DEPTH 2860-2966 M) AT SOUTH PARS GAS FIELD. THE PLOT SHOWS THAT SIX FLOW UNITS CAN BE IDENTIFIED AS INDICATED BY THE DIFFERENT LINES

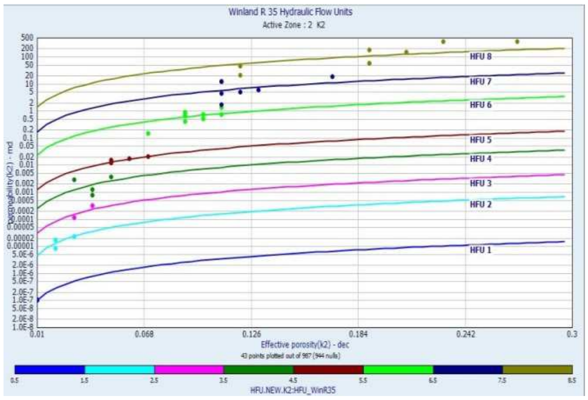

FIGURE. 12. PLOT OF WINLAND R35 SHOWING THE RESULTS OF ASCENDANT HIERARCHICAL CLUSTERING FOR CLASSIFICATION OF WELL LOG DATA FROM THE KANGAN (K2) FORMATION IN TRAINING WELL SP_A (DEPTH 2966-3010 M) AT SOUTH PARS GAS FIELD. THE PLOT SHOWS THAT EIGHT FLOW UNITS CAN BE IDENTIFIED AS INDICATED BY THE DIFFERENT LINES.

E. Pittman R35 method:

The Pittman equations are based on correlation made on around 200 mercury injection PC curves from sandstone plugs. The R value corresponds to the aperture size at a certain mercury saturation (example R30 is the aperture size at 30% mercury saturation). The PC plug pressures were turned into aperture sizes. Then for each equation the aperture for the equation saturation was regressed along with the plugs porosity and permeability to find the fitting coefficients. The equation to use will be the one whose saturation represents the value where the mercury fluid path through the rock becomes continuous. In the Pittman study a saturation of 36% was found to be the average for these sandstones.

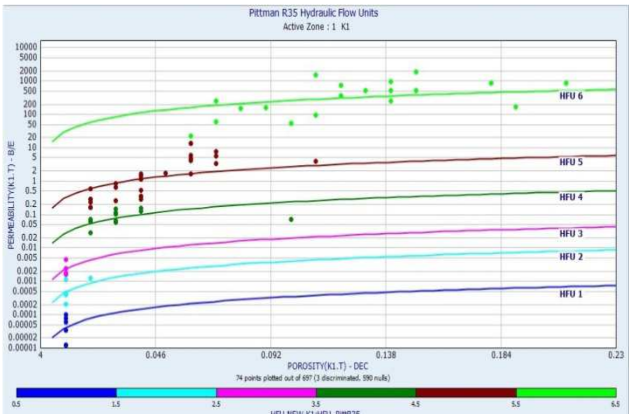

FIGURE 13. PLOT OF PITTMAN R35 SHOWING THE RESULTS OF ASCENDANT HIERARCHICAL CLUSTERING FOR CLASSIFICATION OF WELL LOG DATA FROM THE KANGAN (K1) FORMATION IN TRAINING WELL SP_A (DEPTH 2860-2966 M) AT SOUTH PARS GAS FIELD. THE PLOT SHOWS THAT SIX FLOW UNITS CAN BE IDENTIFIED AS INDICATED BY THE DIFFERENT LINES.

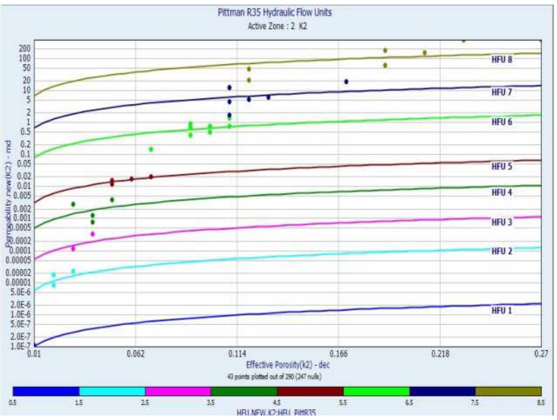

FIGURE 14. PLOT OF PITTMAN R35 SHOWING THE RESULTS OF ASCENDANT HIERARCHICAL CLUSTERING FOR CLASSIFICATION OF WELL LOG DATA FROM THE KANGAN (K2) FORMATION IN TRAINING WELL SP_A (DEPTH 2966-3010 M) AT SOUTH PARS GAS FIELD. THE PLOT SHOWS THAT EIGHT FLOW UNITS CAN BE IDENTIFIED AS INDICATED BY THE DIFFERENT LINES.

III. CORRELATION WELL DATA ANALYSIS AND HFU DETERMINATION

A. AVAILABLE DATA

Total and Effective Porosity and Water saturation data from well SP_A in the South Pars gas field were used in this study. The well log data include gamma-ray (GR), neutron porosity (NPHI), bulk density (RHOB), sonic transit time (DT). well SP_A (2860-3010m) were used for construction of the intelligent models, to evaluate their performance well study zonation to two member based on specification reservoir K1(depth 2860-2966m) and k2(depth 2966-3010m).

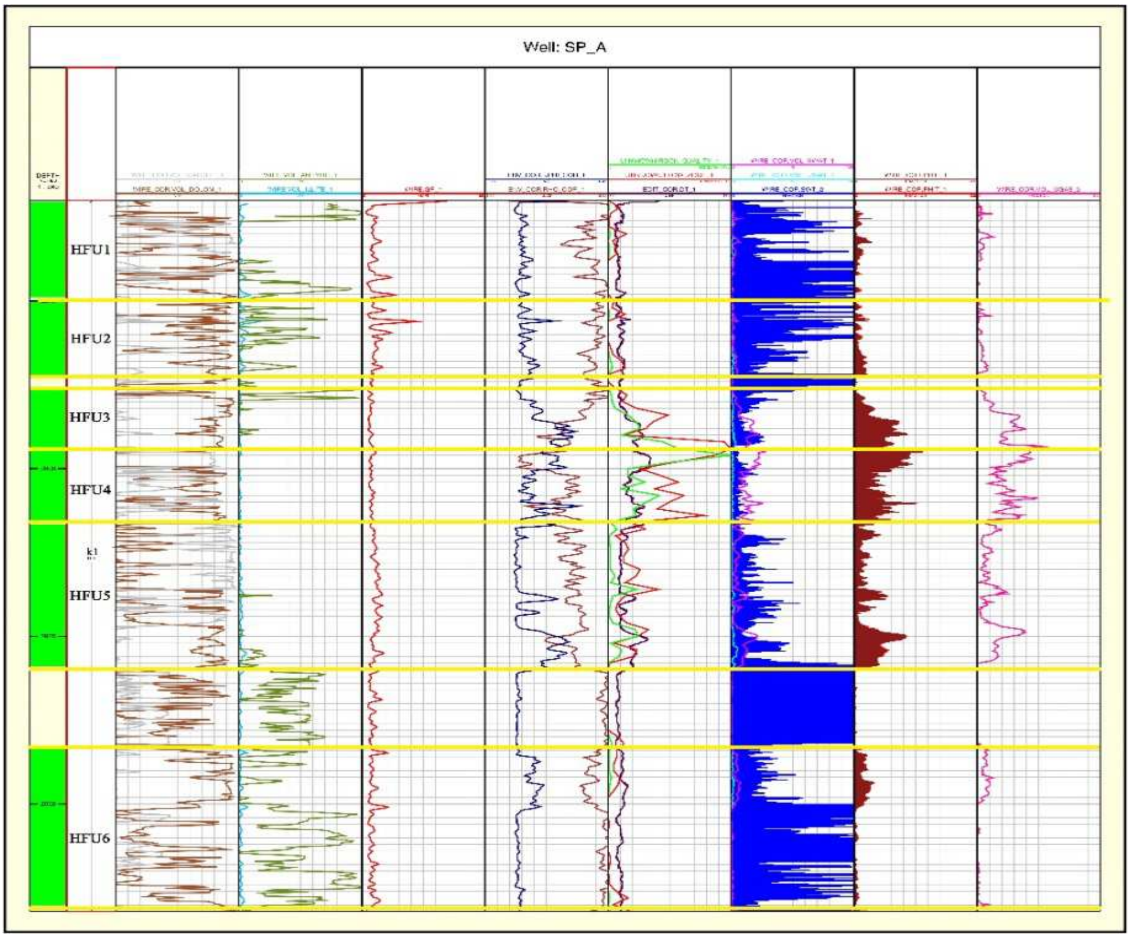

FIGURE. 15. CORRELATION WELL DATA ANALYSIS AND HFU IDENTIFY FROM KANGAN (K1) FORMATION IN TRAINING WELL SP_A (DEPTH 2860-2966 M) AT SOUTH PARS GAS FIELD. THE PLOT SHOWS THAT SIX FLOW UNITS CAN BE IDENTIFIED AS INDICATED BY THE GREEN SECTION.

TABLE1. HFU CHARACTERIZATION FROM WELL DATA ANALYSIS KANGAN (K1) FORMATION IN TRAINING WELL SP_A (DEPTH 2860-2966 M) AT SOUTH PARS GAS FIELD.

Kangan Zone K1	Depth (m)	Thickness (m)	RQI (μm)	FZI (μm)	PHIZ (Fraction)	PHIE (Fraction)	K (md)	SW_{IR} (Fraction)	U_{GAS} (%)	Qualitative Description
HFU 1	2860-2874.607	13.758	1.1047	67.93	0.01626	0.016	1.3E-05	0.09	9.95	Very Good Quality Reservoir(VGQR)
HFU 2	2875.030-2886.037	11.007	0.3963	16.836	0.0235	0.023	0.00014	0.08	1.50	Medium Quality Reservoir(MGQR)
HFU 3	2888.154-2896.515	8.361	0.00628	0.0565	0.1111	0.1	2.496	0.05	9.62	Extremely Good Quality Reservoir(EGQR)
HFU 4	2896.832-2907.839	11.007	0.0016	0.0099	0.1627	0.14	52.213	0.03	13.38	Extremely Good Quality Reservoir (EGQR)
HFU 5	2908.156-2929.535	21.379	0.0225	0.3530	0.0638	0.06	0.116	0.05	5.57	Extremely Good Quality Reservoir(EGQR)
HFU 6	2941.282-2965.095	23.813	0.8431	41.314	0.0204	0.02	2.8E-05	0.12	1.37	Medium Quality Reservoir(MGQR)

Correlation well data analysis and HFU characterization from Kangan formation in K1 reservoir zone shows that HFU5, HFU4 and HFU3 have better quality than the other HFUs determined. K1 reservoir zone in HFU5, HFU4 and HFU3 have higher specification reservoir such as porosity, Permeability and percentage of gas saturation while the water saturation decreases. The HFU discussed above, from the perspective lithology mostly consist of dolomite bearing calcite and have a lower volume of elite. The good combination lithology for capacity of storage and also ability to capacity of flow with suitable specification reservoir causes that HFUs referred have extremely good potential to produce hydrocarbon.

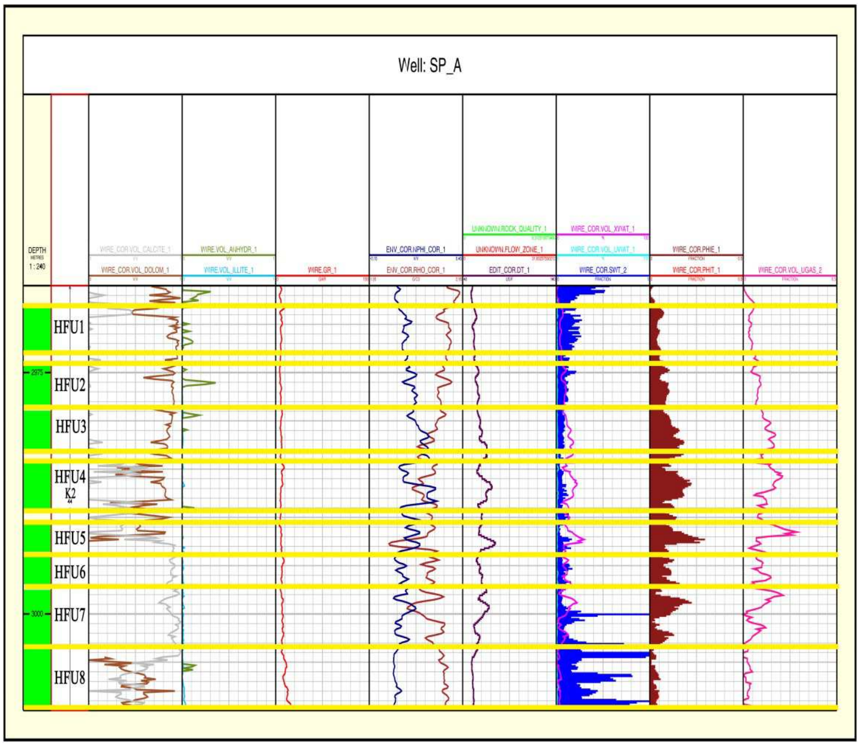

FIGURE.16 . CORRELATION WELL DATA ANALYSIS AND HFU IDENTIFY FROM KANGAN (K2) FORMATION IN TRAINING WELL SP_A (DEPTH 2966-3010 M) AT SOUTH PARS GAS FIELD. THE PLOT SHOWS THAT EIGHT FLOW UNITS CAN BE IDENTIFIED AS INDICATED BY THE GREEN SECTION.

TABLE 2. HFU CHARACTERIZATION FROM WELL DATA ANALYSIS KANGAN (K2) FORMATION IN TRAINING WELL SP_A (DEPTH 2966-3010 M) AT SOUTH PARS GAS FIELD.

Kangan Zone K2	Depth (m)	Thickness (m)	RQI (µm)	FZI (µm)	PHI Z (Fraction)	PHIE (Fraction)	K (md)	SW_{ir} (Fraction)	U_{gas} (%)	Qualitative Description
HFU 1	2968.095-2973.048	4.953	0.0426	0.8105	0.0526	0.05	0.0270	0.06	4.01	Good Quality Reservoir(GQR)
HFU 2	2973.873-2978.318	4.445	0.0177	0.2045	0.0869	0.08	0.2493	0.081	7.50	Very Good Quality Reservoir(VGQR)
HFU 3	2978.762-2983.081	4.319	0.0039	0.0261	0.1494	0.13	8.3678	0.06	13.46	Extremely Good Quality Reservoir(EGQR)
HFU 4	2984.033-2989.304	5.271	0.00162	0.0099	0.1627	0.14	52.213	0.03	13.57	Extremely Good Quality Reservoir (EGQR)
HFU 5	2990.700-2993.494	2.794	0.00136	0.0077	0.1764	0.15	78.98	0.03	13.96	Extremely Good Quality Reservoir (EGQR)
HFU 6	2993.558-2997.114	3.556	0.0098	0.0992	0.098	0.09	0.921	0.06	9.38	Very Good Quality Reservoir(VGQR)
HFU 7	2997.368-3003.210	5.842	0.0079	0.0794	0.1001	0.091	1.417	0.05	8.14	Very Good Quality Reservoir(VGQR)
HFU 8	3003.655-3009.560	5.905	0.3824	12.366	0.0309	0.03	0.0002	0.15	2.08	Medium Quality Reservoir(MGQR)

Correlation well data analysis and HFU characterization from Kangan formation in K2 reservoir zone shows that HFU6, HFU5, HFU4 and HFU3 have extremely good conditions of reservoir. HFUs referred have lower water saturation than the other HFUs and the perspective lithology mostly consist of dolomite bearing anhydrite and have lower volume of Calcite and illite. Well SP_A in K2 reservoir zone have a higher potential to produce hydrocarbone into the K1 reservoir zone.

Correlation well data analysis and HFU characterization from Kangan formation ,The K2 reservoir zone have a very good potential to produce of gas.

IV. CONCLUSION:

This case study clearly shows that the rock typing and Porosity-Permeability modified in various methods can be very effective in building a reliable simulation models. The main conclusions are as follows:

1. Based on various methods for determination HFUs in well SP_A in two reservoirs K1 and K2 respectively they are six and eight HFUs.
2. HFUs determined by different methods for the studied well, total of fourteen hydraulic flow units have been selected. Also HFU5 & HFU4 and HFU3 in K2 reservoir zone and HFU5 and HFU4 have extremely good quality reservoir.
3. According to data analysis and HFU characterization, K2 reservoir zone have very good potential to produce gas hydrocarbon.
4. By comparison of various methods for determination of HFUs, the histogram of Flow Zone Indicator and the Advanced Lorenz plot resulted better performance. Because applying the heterogeneity by the Advanced Lorenz plot on real data, could determine distant HFUs for each zone.
5. Application of the above methods could show higher heterogeneity for the k2.
6. Applying the above methods, could help for better interpretation and better understanding of well perforation.

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