Hydraulic flow units for reservoir characterization: A successful application on arab-d carbonate

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Abstract. The characterization of carbonate formations is challenging as compared to sandstones, yet carbonate reservoirs hold over 60% of the world’s hydrocarbon reserves. Carbonate reservoirs exhibit a high level of heterogeneity at every scale; from core to field. To be able to manage heterogeneity for reservoir modelling, the formation has to be discretized into a few rock types, each of which having somewhat similar flow properties. Recently, the interest in extending the rock-typing approaches is increasing with the aim to identify the potential layers in complex lithology like carbonates. The approach becomes more rigorous if the geological description is coordinated with petrophysical data, an approach that has been followed in this study. The hydraulic flow units in Arab-D formation were identified and interpreted using both geological facies and petrophysical data. All three methods; histogram analysis, normal probability plot and least-squared regression were utilized to determine the optimum number of hydraulic flow units across Arab-D carbonate formation. Published routine core analysis data from ten wells of Arab-D formation was analyzed and six optimum hydraulic flow units were identified. The average porosity and average permeability of each hydraulic flow unit was then computed. The results were found to be in good agreement with the geological facies data of the Arab-D formation, thus validating the identified flow units.

1. Introduction
Characterization of carbonate reservoirs is challenging due to The existence of heterogeneities at each scale caused by diagenesis [1]. In the past years, there have been many attempts to establish a universal workflow to characterize carbonates using both geological and petrophysical data. However, many of these approaches are not rigorous enough in integrating all data and are inadequate for up-scaling [2]. Hydraulic flow units (HFU) is one of the most widely used to accurately describe and characterize carbonate reservoirs [3-5]

Hydraulic flow unit (HFU) is defined as a rock volume unit whose members have somewhat similar flow properties which are distinct from properties in the other units. The concept of HFU is different than lithofacies as it aims to cluster similar fluid pathway in the reservoir rather than on the basis of distribution of lithologies [6]. HFU can be determined by making use of rock quality index, void ratio and flow zone indicator (Equations 1 to 3) which also relate to the mean hydraulic radius [7, 8]. The reservoir quality index (RQI) is defined as the ratio of permeability to porosity:

\[ RQI = 0.0314 \sqrt{\frac{k}{\phi}} \]  

(1)

The void ratio or the normalized porosity, \( \phi_z \) is defined as:
\[ \varphi_z = \frac{\varphi}{1-\varphi} \]  \hspace{1cm} (2)

By excluding the microscopic measurement parameters and lumping the Carmen-Kozeny parameters, a variable called Flow zone indicator (FZI) can be introduced, which is a function of reservoir quality index (RQI) and void ratio:

\[ FZI = \frac{RQI}{\varphi_z} \]  \hspace{1cm} (3)

Where RQI is the rock quality index (μm), k is permeability (mD), is effective porosity (v/v), \( \varphi_z \) is normalized porosity, and FZI is the flow zone index (μm).

By taking log on both sides of Equation 3 and re-arranging:

\[ \log \text{RQI} = \log \text{FZI} + \log \varphi_z \]  \hspace{1cm} (4)

Equation 4 suggests that log-log plot of RQI versus \( \varphi_z \) should yield straight line of which the slope is one and the intercept equals FZI. Rocks that falls on the same straight line are considered to be in the same hydraulic flow unit, with a unique value of FZI obtained from the intercept.

This concept has been employed by many researchers to characterize giant carbonate reservoirs in USA, Russia, and Middle East [9-12]. However, none of these studies had linked the petrophysical properties hydraulic flow units (HFUs) to their corresponding geological data. In this study, the concept of hydraulic flow unit (HFU) is implemented to characterize the prolific Arab-D carbonate formation. In doing so, around 480 published routine core analysis data (RCA) were collected and used for this purpose [13]. The RCA data included porosity, permeability, grain matrix density, and facies descriptions for 480 core plugs.

2. Geological background

Figure 1 shows Ghawar field which is the world’s largest oilfield located in Saudi Arabia at about 200 km east of Riyadh.

![Image of Ghawar field and study area](image-url)

**Figure 1.** Location of Ghawar field and study area [11].

The field is 280 km long and 30 km wide on average. It is divided into six areas which are Fazran, Ain Dar, Sheddum, uthmaniyah, Haradh and Hawiyah from North to South. The field covered with
mainly sediments from Miocene-Pleistocene with two small outcrops of Eocene. Upper Jurassic Arab formation constitutes of four main members (from bottom to top): Arab-D, Arab-C, Arab-B, and Arab-A. The main reservoir in Ghawar field is the carbonate part of the Arab-D. The Arab D formation is mainly made up of packstone and grainstone with underlying formation of Jubaila which consists of limestone and mudstones with an average porosity of 15%. Dolomites also occur in the formation with very high permeability contributing to high production rates. Along Arab-D formation, six lithofacies were reported; namely Skeletal Oolitic Above Sequence Boundary, Cladocoropsis, Stromatoporoid-Red Algae-Coral, Skeletal Oolitic Below Sequence Boundary, Bivalve-Coated Grain-Intraclast and Micrite [13, 14].

3. Methodology
The optimum number of hydraulic flow units (HFU) across Arab-D formation were identified using the 480 routine core analysis (RCA) data. As in Figure 2, Histogram analysis, probability analysis and linear regression were the three methods employed for this purpose. Histogram analysis of flow zone indicator (FZI) data was first implemented to get a quick identification of the number of existing hydraulic flow units. The FZI data were then analyzed using probability analysis method. Lastly, several iterations of the linear regression analysis between rock quality index (RQI) and normalized porosity ($\phi_Z$) were conducted to find the optimum number of HFUs. The correlation coefficients of regression ($R^2$) were calculated and the optimum number of HFU’s were deduced when no significant change in correlation coefficients between RQI and $\phi_Z$ occurred (Figure 5). The porosity and permeability data belonging to each HFU was then averaged to represent its $k-\phi$ value. To validate the findings, the characteristics of the arbitrarily identified HFU’s were correlated against the geological facies data for the reservoir and a good agreement was found.

![Figure 2. Work flow chart for finding optimum rock clusters based on HFUs.](image)

The following sections will further elaborate the three method.

3.1. Histogram analysis method
The histogram analysis method serves as a primary method to identify the number of HFU’s existing in a heterogeneous carbonates reservoirs. Since FZI is an indirect function of permeability, a histogram of log FZI would reveals “n” numbers of normal distributions corresponding to “n” numbers of HFU’s. In this research, the flow zone index (FZI) values were first calculated using equation 2. A histogram plot for FZI value is then constructed. The number of HFU’s corresponds to the number of normal distributions in the histogram plot of Log (FZI). A new FZI is determined to represent each HFU by averaging all the FZI within the same HFU.
3.2. Probability analysis method
The probability method is applied for more investigation. The data of Log FZI was plotted versus the percentile in a normal probability plot. The number of optimum HFU’s was revealed by the number of significant straight lines observed in the normal probability plot.

3.3. Least square regression method
Least square regression method was also utilized to identify the optimum number of existing HFU’s. Rock quality index (RQI) and normalized porosity ($\varphi_Z$) values were calculated using equation 1 and equation 3. In a log-log scale, a plot of RQI versus $\varphi_Z$ was then constructed. Initially, it was assumed that only one HFU exists and the coefficient of determination ($R^2$) was calculated. In the same way, the process was repeated by assuming a higher number of HFU’s until there is no significant change in $R^2$ values. In this method, each HFU is represented by straight line with unit slope in the log-log plot of RQI versus $\varphi_Z$. Once the optimum number of HFU’s were confirmed, the k-$\phi$ transforms were established and validated with the geological information of cores.

4. Results & discussion

4.1. Optimum number of hydraulic flow units
Three methods were used to identify the optimum number of hydraulic flow units (HFU) that can be presumed to exist in the “Arab D” formation. The analyses using each of these methods is presented here along with a comparison of their efficacy.

4.1.1. Analysis by histogram method
Figure 3 is histogram plot of log FZI as plotted using method explained in section 3.1. It is obvious from the plot that more than one flow units exists in Arab-D formation. However, it is difficult to identify the exact number of flow units existing in this formation because the histogram plot of log FZI is a superposition of a number of overlapping individual normal distributions. Unless the number of individual distributions is isolated/identified, one cannot predict the number of existing hydraulic flow units. Since the accuracy of this method is influenced by transition zones between HFU’s, the analysis of “Arab D” flow units using histogram method is a qualitative one that show only that a variation in the distribution of HFU’s across Arab-D formation exists.

![Figure 3. Histogram plot of log FZI (Flow Zone Indicator).](image)

4.1.2. Analysis by probability plot method
The results of this method are quantitative and more accurate than histogram method. Figure 4 is the normal probability plot of log FZI. Six distinct straight lines can be identified when log FZI is plotted on a log normal probability plot which suggests the existence of six HFU’s along Arab-D formation.

**Figure 4.** Normal probability plot of log FZI

4.1.3. Analysis by least-square regression method

This is a more rigorous/accurate quantitative method for establishing optimum number of HFUs and determining the porosity-permeability relationships for each identified HFU. Figure 5 was constructed to unravel the optimum number of existing HFUs. Initially, one single HFU was assumed to exist in the whole Arab –D formation. The permeability–porosity relationship was then established and the predicted permeability was correlated with the permeability data from routine core analysis (RCA) and the value of coefficient of determination (denoted by $R^2$) was determined by regression analysis. $R^2$ value ranges between 0 and 1 indicating the extent to which the dependent variable is predictable. The $R^2$ determined for 1-HFU assumption for Arab-D was 0.75, which indicates a fair degree of correlation. The above process was repeated by increasing the number of HFUs by one and determining the $R^2$ for the corresponding number of HFU. The two $R^2$ values were plotted in a $R^2$ vs Number of HFUs graph. This process was continued until increasing the number of HFU further did not improve the $R^2$ value i.e. the curve leveled off. A careful examination of the completed plot (Figure 5) reveals that the curve levels off when the number of HFUs is six. Thus, considering number of HFUs more than six will not improve the analysis and six is the optimum number.

**Figure 5.** Coefficient of determination versus number of HFU’s
To determine the porosity-permeability relationship of each HFU, the reservoir quality index (RQI) was calculated using the porosity-permeability data from core analysis and applying Equation 1. Also, the porosity data was normalized by using Equation 3 and is denoted by $\phi_Z$. The FZI value for each data point was calculated using Equation 3. The data was clustered into six (the optimum number of HFUs) by choosing appropriate ranges of FZIs for each HFU. The average FZI was then computed for each HFU cluster. Figure 6 shows the RQI versus normalized porosity ($\phi_Z$) data plotted on a log-log scale. To draw a line for each HFU, a straight line of slope 1 was constructed and pinned at the corresponding average FZI as intercept (the intersection of straight line at $\phi_Z = 1$ since it is a log-log plot).

![Figure 6. Reservoir quality index vs normalized porosity](image-url)

The RQI value of the HFUs is read at the intersection of the straight line to RQI scale at the origin. Having the HFUs identified and verified by Figure 7, the average porosity and average permeability values were determined by taking an average of all the data belonging to an HFU. Table 1 shows the predicted porosity and permeability values for each of the determined flow units.

| HFU# | Average Permeability (mD) | Average Porosity (%) |
|------|--------------------------|----------------------|
| 1    | 1789                     | 19                   |
| 2    | 451                      | 22                   |
| 3    | 90                       | 22                   |
| 4    | 10                       | 19                   |
| 5    | 0.333                    | 9                    |
| 6    | 0.009                    | 6                    |

4.1.4. Validating the characterization
To validate the results, the predicted HFU’s were combined with the existing lithofacies’ description from the Rosetta stone project. For example, Figure 6 indicates that the dominant Lithofacies in HFU 1 are Skeletal-oolitic packstone, which was reported to possess a horizontal permeability up to 1451 (mD) in a core scale[13]. The poor permeability in HFU 5 and HFU 6 is attributed to micrite which was found to be the abundant lithofacies existing in those two hydraulic flow units. Thus, these results are in good general agreement with the predicted properties of hydraulic flow units as in Table 1.

![Figure 7. Lithofacies of each HFU.](image)

5. Conclusions
Based on the case study of Arab D” formation, following observations/conclusion can be made:

- Clustering the rocks into families with similar flow properties (HFU) is a viable tool for reservoir characterization of carbonate reservoirs.
- Histogram analysis of FZI data is a qualitative approach but has limitations since it can’t identify the optimum number of HFU’s objectively, thus its use as a stand-alone technique be avoided.
- Probability analysis of FZI data is a quantitative approach which gives satisfactory results. However, it should be used in conjunction with the “Least Square Regression” to improve the confidence level.
- “Least Square Regression” method is probably the most rigorous method for determining the HFUs which can be used as a standalone method.
- For future studies, artificial intelligence and data science tools should be implemented for such characterizations. This would be more efficient.

6. References
[1] A. S. Bagci and C. Y. Akbas, "Permeability Estimation Using Hydraulic Flow Units in Carbonate Reservoirs," in Rocky Mountain Oil & Gas Technology Symposium, 2007.
[2] M. Rebelle, "Rock-typing In Carbonates: A Critical Review Of Clustering Methods," in Abu Dhabi International Petroleum Exhibition and Conference, 2014.
[3] J. Radiansyah, T. E. Putra, R. Ismail, R. A. Wibowo, E. E. Riza, and M. Kurniawan, "Reservoir Description using Hydraulic Flow Unit and Petrophysical Rock Type of PMT Carbonate Early Miocene of Baturaja Formation, South Sumatra Basin," in Adapted from extended abstract prepared in conjunction with presentation AAPG International Conference & Exhibition, Istanbul, Turkey, 2014.
[4] R. Mohebian, M. A. Riahi, and A. Kadkhodaie, "Characterization of hydraulic flow units from seismic attributes and well data based on a new fuzzy procedure using ANFIS and FCM algorithms, example from an Iranian carbonate reservoir," *Carbonates and Evaporites*, pp. 1-10, 2017.

[5] S. K. Mahjour, M. K. G. Al-Askari, and M. Masihi, "Flow-units verification, using statistical zonation and application of Stratigraphic Modified Lorenz Plot in Tabnak gas field," *Egyptian Journal of Petroleum*, vol. 25, pp. 215-220, 2016.

[6] W. Ebanks Jr, "Flow unit concept-integrated approach to reservoir description for engineering projects," *AAPG (Am. Assoc. Pet. Geol.) Bull.; (United States)*, vol. 71, 1987.

[7] A. A. Abed, "Hydraulic flow units and permeability prediction in a carbonate reservoir, Southern Iraq from well log data using non-parametric correlation," *Int J Enhanc Res Sci Technol Eng*, vol. 3, pp. 480-486, 2014.

[8] N. Bize-Forest, V. Baines, A. Boyd, A. Moss, and R. Oliveira, "Carbonate Reservoir Rock Typing and the Link between Routine Core Analysis and Special Core Analysis," in *International Symposium of the Society of Core Analysts*, 2014, pp. 8-11.

[9] D. A. Alobaidi, "Permeability Prediction in One of Iraqi Carbonate Reservoir Using Hydraulic Flow Units and Neural Networks," 2016.

[10] O. Deghirmandjian, "Identification and characterization of Hydraulic Flow Units in the San Juan Formation, Orocuca Field, Venezuela," Texas A&M University, 2001.

[11] F. A. Al-Ajmi and S. A. Holditch, "Permeability Estimation Using Hydraulic Flow Units in a Central Arabia Reservoir," 2000.

[12] A. Kassenov and Z. Uzykanov, "Application of Hydraulic Flow Units for History Matching of the Hydrodynamic Model of Tengiz Field," in *SPE Annual Caspian Technical Conference & Exhibition*, 2016.

[13] E. A. Clerke, H. Mueller, E. C. Phillips, R. Y. Eyvazzadeh, D. H. Jones, R. Ramamoorthy, *et al.*, "Application of Thomeer Hyperbolas to decode the pore systems, facies and reservoir properties of the Upper Jurassic Arab D Limestone, Ghawar field, Saudi Arabia: A “Rosetta Stone” approach," *GeoArabia*, vol. 13, pp. 113-160, 2008.

[14] R. Sorkhabi. (2010, September 2010) The King of Giant Fields. *GEO ExPro [Geoscience]*. 88.