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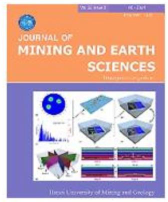

Hydraulic flow unit classification from core data: case study of the Z gas reservoir, Poland

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ABSTRACT

Permeability and porosity are essential parameters for estimating hydrocarbon production from reservoir rocks. They are combined in an additional factor, the Flow Zone Index (FZI), which is the basis for defining the hydraulic flow unit (HFU). Each HFU is a homogeneous section of a reservoir rock with stable parameters that allow for media flow. Hydraulic flow units are determined from the porosity and permeability of core or well logs. The simple statistical methods are applied for HFU classification and then improve permeability prediction. This paper also shows how to quickly apply the global hydraulic elements (GHE) method for HFU classification. The methodology is tested on the Miocene formation of a deltaic facies from the Carpathian Foredeep in South-Eastern Poland.

1. Introduction

Porosity and permeability are two properties of reservoir rock that strongly influence the movement of media in the rock's pore space. Formulas for permeability vs porosity defined by Cozeny and Carman (1927, 1937) are the most known equations used to describe water and hydrocarbon ability to move throughout the pore space of rock. Improved lab equipment and logging devices provide relatively good data, but it is still difficult to parameterize factors such as tortuosity, specific surface, or the radius of pores in a rock formation. To overcome these difficulties, the parameters of Flow Zone Index (FZI) and then Hydraulic Flow Unit (HFU) are defined as primary parameters that implicitly describe the ability of media to flow in the pore space of reservoir rock.

Our goal is to prepare petrophysical data for modelling media flow in the pore space of reservoir rock. The rock formation represented by core parameters and log data is divided into homogeneous hydraulic flow units. Core data will be used to calculate the Flow Zone Index (FZI) in cored sections of the wells and then apply some

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statistics method for HFU classification basic on FZI mean value. In this study, we also apply the Global Hydraulic Element (GHE) method introduced by (Corbett et al., 2003, 2004; Matyasik et al., 2007) for a rapid and more straightforward approach to plot the porosity and permeability data on the predetermined GHE template.

2. Geological setting and data set

2.1. Geological setting

The majority of gas deposits recognized in the Carpathian Foredeep basin occurred in the Miocene strata. Most of them are small but economically important. Generally, in all deposits, good reservoir properties are observed. The Z gas field was discovered in the early 60 of the 20th century in the Northern part of the Carpathian ForedeEquation The main gas horizons occurred in the upper part of the Sarmatian argillaceous - arenaceous sequences at a depth interval between 390 and 545 m. Good reservoir parameters were observed. The deeper productive horizons were discovered on the basis of a new approach to the seismic anomalies interpretation in the latest 90. Now, the Z gas field is recognized in three parts: Eastern, central, and western. Productive horizons are discovered in the whole profiles of wells in the Sarmatian deposits (Figure 1).

The Z gas reservoir, like many others in the Carpathian Foredeep, is multi-horizontal. Sequences of thin shale laminas are sealing gas horizons in thin sandstone strata and prevent the movement of gas up to the top of sedimentary systems. Porous sandstones of high permeability belong to depositional elements of submarine fans, sandstones of deltaic environments (largemouth bars, distributor channels, and others), shallow marine clastic deposits of estuaries, and sandy barriers. In those horizons sandstones with gas are difficult to recognize because of the low contrast of parameters between sandstones and shales. Deltaic sediments are well recognized in the Carpathian Foredeep. Sandstone reservoirs distribution in the Z gas field is of very good reservoir parameters (Mysliwiec, 2006; Mysliwiec et al., 2004).

2.2. Data set

Core data from wells in the Z gas field in the NE Polish part of the Carpathian Foredeep were available (Figure 1). Laboratory core measurements included effective porosity (Φe) and absolute permeability (K), which were taken from various depths in the selected wells. The study dataset included 570 core samples from 11 wells, and the core interval ranges from 253 m to 1154 m. Only three samples were taken from littoral facies at a depth between 253÷272 m, and the other one was taken from a deeper part section.

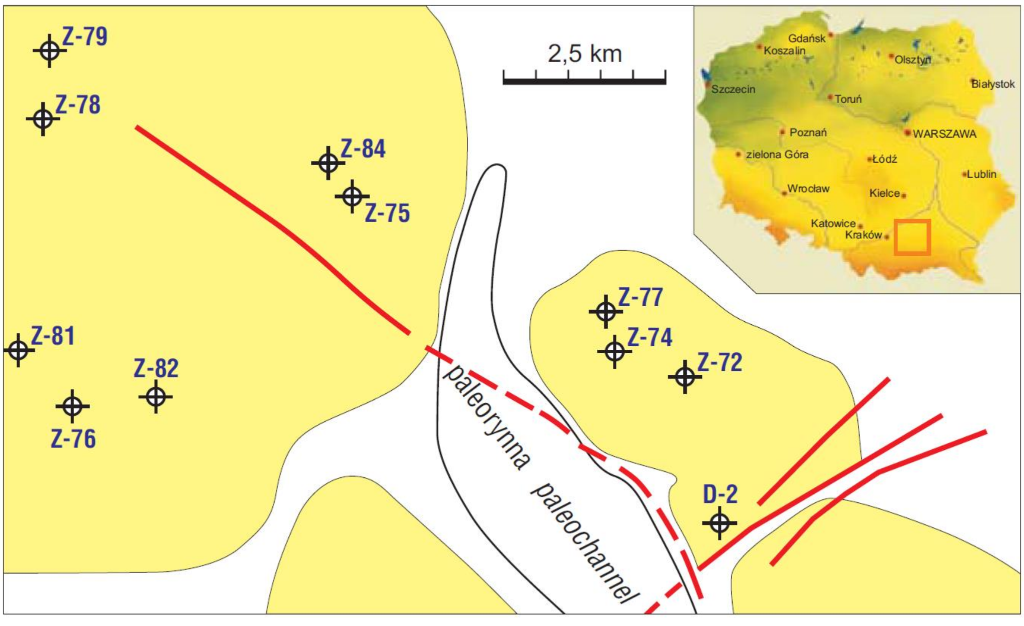

Figure 1. Location of the Z gas - field with the 11 wells location (after Mysliwiec, 2006; Mysliwiec et al., 2004).

All primary statistical analyses, i.e., Histogram of porosity (Figure 2a), permeability (Figure 2b), FZI (Figure 2c), and cross plot of permeability versus porosity for 570 cores data (Figure 2d) were performed on the full data set. Most of the samples were obtained in deltaic sandy - muddy - shaly deltaic facies

3. Methodology

3.1. Hydraulic Flow Unit - HFU

The concept of hydraulic flow unit was introduced by Ebanks et al. (1987, 1992), who defined an HFU 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. He described the flow units as the following:

- A specific volume of a reservoir; it is composed of one or more reservoir - quality lithology and any none - reservoir - quality rock types within that same volume, as well as the fluids they contain,
- A correlative and mappable unit at the interwell scale,
- A recognizable section on wireline logs,
- A unit is being in communication with other flow units. However, flow units based on lithostratigraphic characteristics are not always in pressure communication (Figure 3).

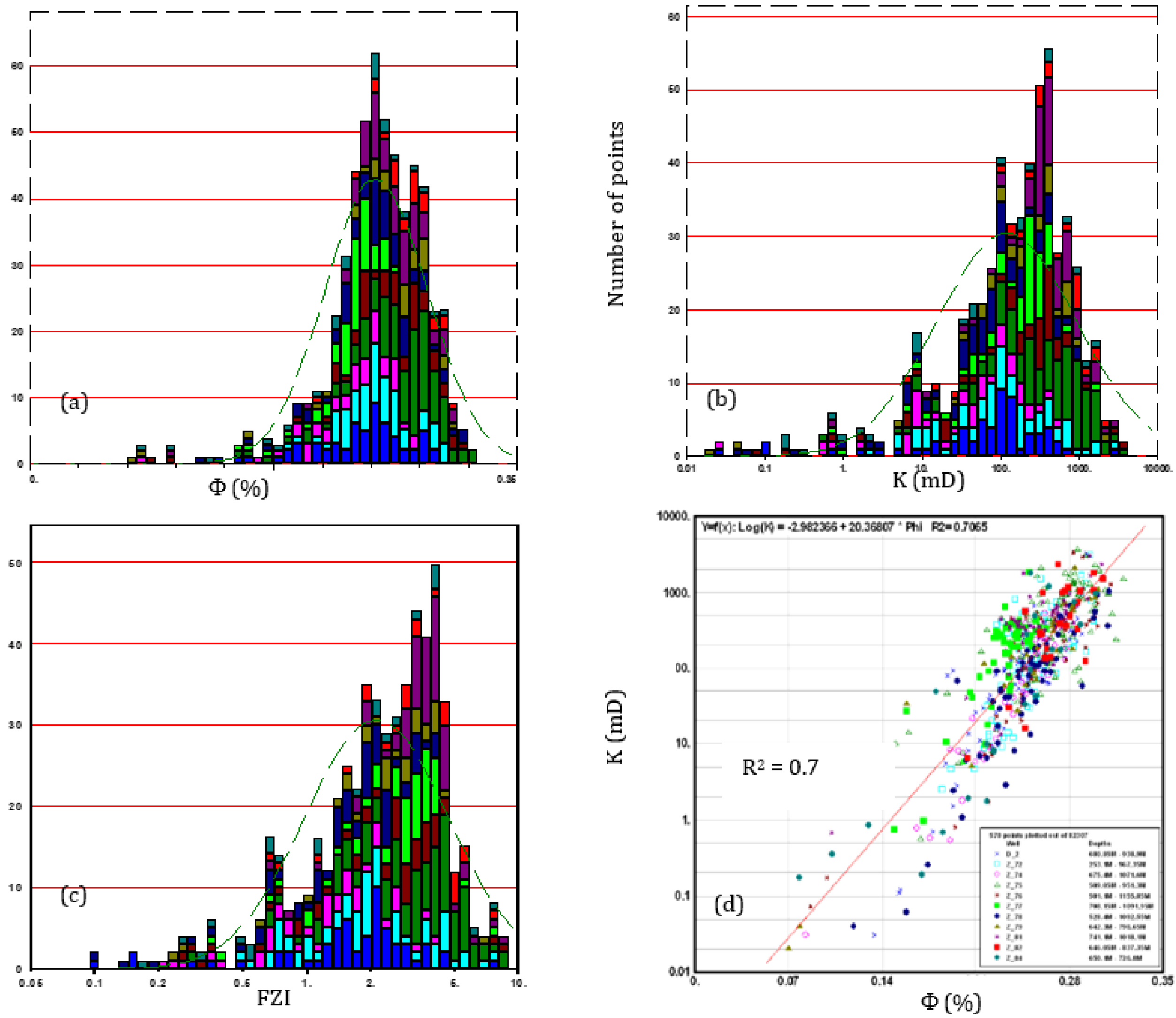

Figure. 2. Histogram of porosity (a), permeability (b), FZI (c), and cross plot of log permeability versus porosity for 570 cores data (d).

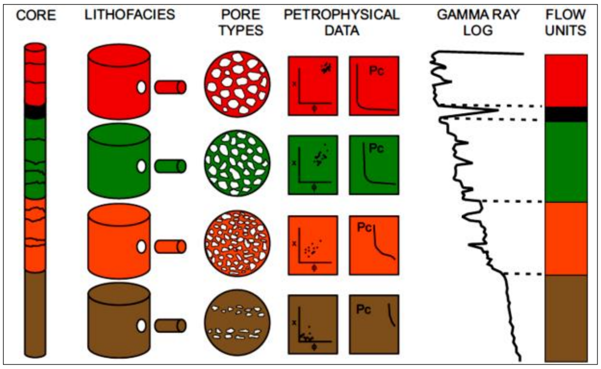

Figure 3. Various parameters are used in defining geologic flow units; the flow units are defined based on lithofacies, pore types, porosity, and permeability cross - plots, capillary pressure measurements, and gamma - ray log response (after Ebanks et al. 1992).

The structure, texture, and mineral composition of rock formation strongly influence the relationship between porosity and permeability. Petrophysicists working for the oil and gas industry and prospecting hydrogeology and geothermal water reserves prospecting try to find the best relationship between those two reservoir parameters since the times of Kozeny (1927) and Carman (1937). A breakthrough was noted with an approach based on the FZI proposed by Amaefule et al. (1993), which was then followed by other authors (Prasad, 2000). FZI is a derivative factor determined based on the generalized Cozeny - Carman equation:

$$k = \frac{\phi^3{}_e}{(1-\phi_e)^2}\left[\frac{1}{F_s\tau^2 S^2{}_{gv}}\right] \quad (1)$$

where: K - the permeability; Φ_e - the effective porosity; F_s - the shape factor; τ - the tortuosity of pores; S_{gv} - the specific surface.

Amaefule et al. (1993) introduced two auxiliary factors: Φ_z, the normalized porosity (Equation 2), and RQI, the reservoir quality index (Equation 3). This results in a new formula (Equation 4), which is a definition of FZI.

The basis of HFU classification is to identify groups of data that form the unit - slope straight lines on a log - log plot of RQI versus Φ_z. The permeability of a sample point is then calculated from a pertinent HFU using the mean FZI value and the corresponding sample porosity using the following Equation (5).

$$\phi_z = \left(\frac{\phi_e}{1-\phi_e}\right) \quad (2)$$

$$RQI = 0.0314\sqrt{\frac{k}{\phi_e}} \quad (3)$$

$$FZI = \frac{1}{\sqrt{F_s}\tau S_{gv}} = \frac{RQI}{\phi_z} \quad (4)$$

$$K = 1014.24(FZI)^2\frac{\Phi_e{}^3}{(1-\Phi_e)^2} \quad (5)$$

On the basis of Equations (Equation 1÷4), we assume that units of constant FZI have invariable reservoir parameters that differ from the surrounding neighbourhood. Proper division of the data set into units of constant FZI forms the basis for the HFU construction, resulting in the best partial relationships of permeability vs porosity for each HFU.

3.2. Global Hydraulic Elements - GHE

Corbett et al. (2003, 2004) proposed the rapid and more straightforward approach to plot the porosity and permeability data on the predetermined global hydraulic elements (GHE) template (Figure 4), which is constructed based on eq. (5). A systematic series of a priori FZI values were arbitrarily chosen to define 10 porosity - permeability elements. Only ten were chosen to split the wide range of porosity and permeability parameter space into a manageable number of GHEs (Table 1).

Data in the study projected on the Corbett and Potter (2004) template shows the close relationship between permeability and porosity in each HFU = GHE. Thus, established equations are used to calculate K from Φ and FZI. The relationship between permeability from the core data and permeability calculated from the means of FZIs in GHE is very close (Figure 4).

4. Results and discussions

Probability function to select number of HFU

To confirm the division of the data set into the

Table 1. Global hydraulic elements (GHE) template parameters (Corbett et al. 2003).

GHE	GHE1	GHE2	GHE3	GHE4	GHE5	GHE6	GHE7	GHE8	GHE9	GHE10
FZI	0.0938	0.1875	0.375	0.75	1.5	3	6	12	24	48

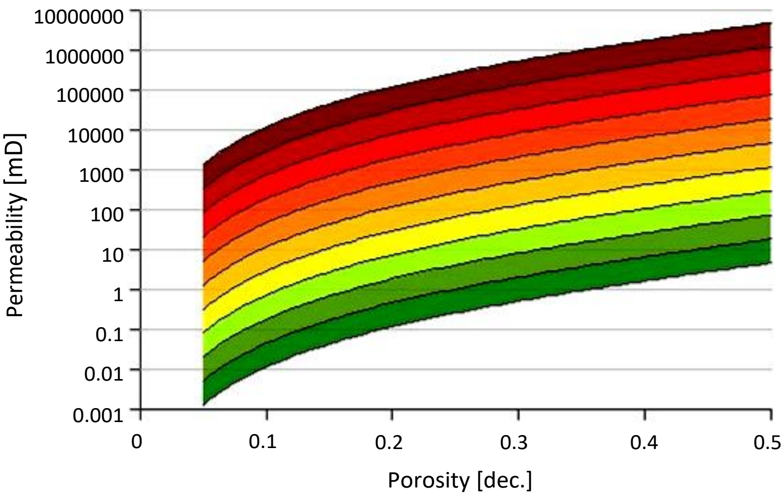

Figure 4. Global Hydraulic Element "basemap" template showing GHE1 to GHE10 (Corbett et al. 2003).

proper number of HFUs the probability function of log(FZI) is calculated. A normal probability plot illustrates how the local slope changes according to selected groups with a constant FZI. In Figure 5.a, six straight lines connecting the selected sections of the probability plot determined six uniforms HFUs.

Clustering the core data

Hierarchical cluster analysis is also applied to agglomerate and differentiate the data (Davis, 1973). Elements belonging together in the group are as similar as possible, and groups are as different as possible from others. Based on Ward's algorithm, the data set of the FZI and HFU is divided into 6 clusters. The three dashed lines show the possible cutoffs for the proposed divisions into 8, 6, 4, and 3 groups. We decided to use six groups (the red line in Figure 5.b).

Because mean FZI values are not calculated from the probability plots or Ward's HFU classification algorithm, a plot of Φ_z vs RQI for each HFU was constructed (Figure 6). The unit slope lines were drawn for each HFU through their data clusters according to the mean value of FZI calculated for each HFU at the intercept with Φ_z = 1. The mean FZI values were then used to construct the porosity - permeability relationship within each HFU using Equation 5. Figure 7 shows the porosity-permeability cross-plot combined with the HFU for all core data. The curves represent the porosity - permeability relationship based on Equation 5 using the mean value of FZI for each hydraulic unit.

Simple statistics of permeability, porosity, and FZI show that the separate uniform groups are unambiguously described by the mean value of FZI (Table 2). For these six defined groups of data, each with homogeneous HFU of constant reservoir parameters, we calculated the equations relating FZI to the permeability and porosity using core data. Finally, the permeability that was calculated based on Equation 5 with mean values of FZI for each HFU was highly correlated to the core origin permeability (Table 2 and Figure 8).

The core porosity and permeability data from the *Z* gas field were projected on the appropriate GHE template constructed for each HFU (Figure 9). It was observed that the data will fit in the prediction processing model. In each HFU/GHE pair, the close relationship between permeability and porosity was established, and those equations were used to calculate *K* from *Φ*. Figure 10 shows a comparison between permeability from the core data and permeability calculated from the 7 GHEs correspondings to 7 FZIs on Table 1.

The GHE results gave approximately the same number of GHEs as the HFU. It was therefore useful to compare the previous conventional approach

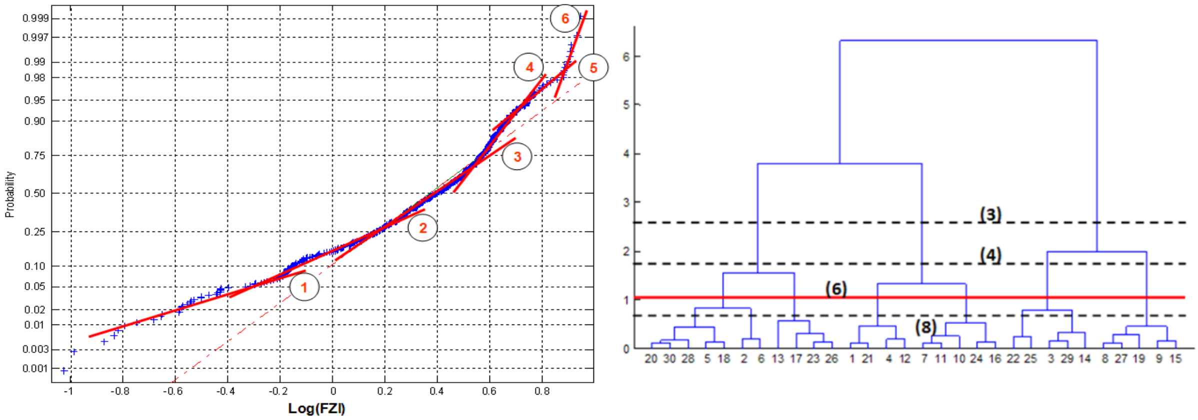

Figure 5. a) Normal probability plot of log(FZI) with division into 6 homogeneous groups of HFU with constant FZI; b) Dendogram of the FZI set into six groups, according to the Ward's algorithm.

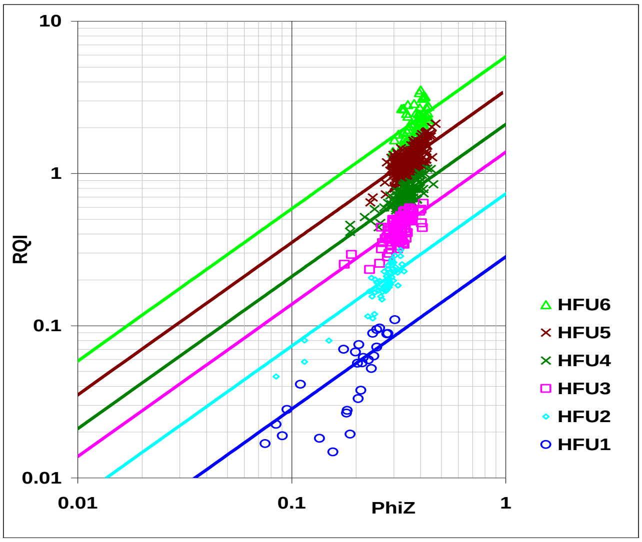

Figure 6. Φz vs. RQI cross-plot of all the hydraulic units. The mean FZI values for each hydraulic unit are given by the intercept of the straight lines at Φz =1.

Table 2. Simple statistics of permeability (K), porosity (Φ), FZI, and the determination coefficients (R^2) for the permeability, calculated from the 6 FZI_mean and 6 HFU.

HUs	Nr. of data in HU	K (mD)			PHI (%)			FZI			R^2 (k_{FZI_mean} vs. $k_{\_core}$)
		min	mean	max	min	mean	max	min	mean	max	
HU1	28	0.02	0.72	2.82	0.07	0.16	0.233	0.095	0.283	0.400	0.728
HU2	58	0.17	9.15	24.33	0.078	0.21	0.251	0.466	0.734	0.971	0.888
HU3	89	9.78	50.75	120.04	0.15	0.24	0.292	0.997	1.379	1.687	0.645
HU4	117	40.470	144.72	358.55	0.203	0.257	0.315	1.733	2.10	2.563	0.743
HU5	214	79.79	445.77	1461.7	0.189	0.26	0.32	2.587	3.51	4.512	0.603
HU6	64	430.07	1458.96	3631.1	0.229	0.27	0.306	4.555	5.85	8.833	0.411
All											0.97

(Figure 7) with the GHE approach (Figure 9) to show that GHEs are a useful concept, and the number of arbitrary GHEs on the template is probably appropriate. In the future, GHEs appear to provide an easy, rapid way of classifying core data.

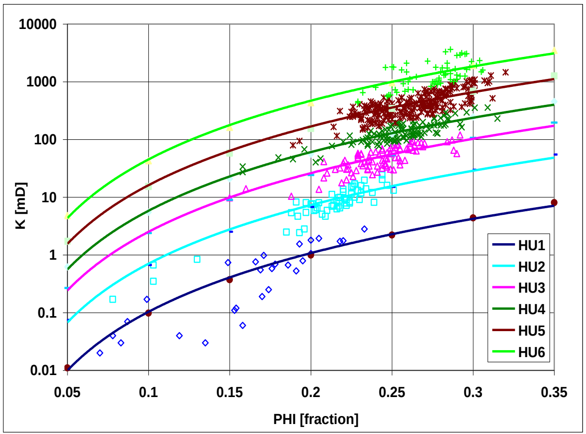

Figure 7. Dispersion plot of Φ_core vs. K_core, and the six HFU defined in the area of core origin data.

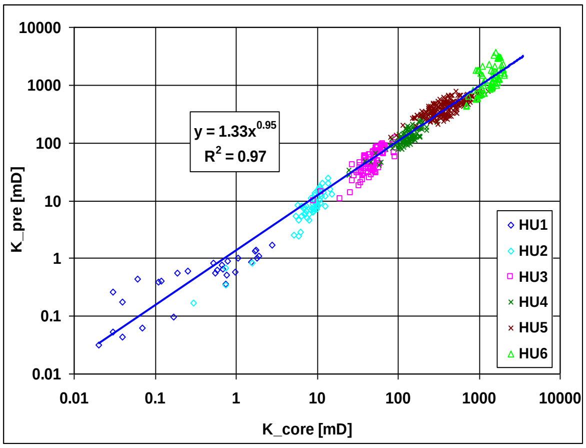

Figure 8. Dispersion plot and correlation line between the core origin permeability (K_core) vs. the permeability calculated (K_pre) from the mean values of FZI for HFU.

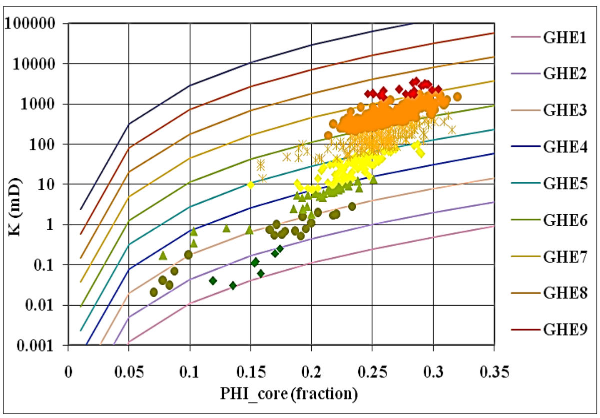

Figure 9. Displaying permeability vs. porosity core data on the background of 10 GHE shows that the Z gas reservoirs can divide to 7 GHE (range from GHE1 to GHE7).

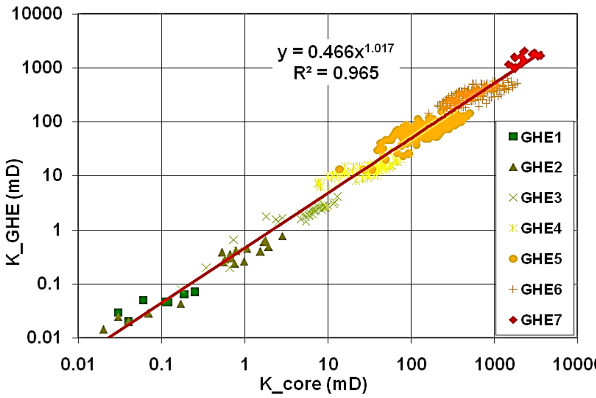

Figure 10. Dispersion plot and correlation line between the core permeability (K_core) vs. the permeability calculated (K_GHE) from the 7 GHEs.

Conclusions

The hydraulic flow unit technique has been developed and applied to identify the reservoir characteristics. This technique has a wide variety of practical field applications to both cored and uncored intervals/wells. In the study, the Z gas reservoirs were classified into 6 HFUs based on 570 core plugs data by applying conventional cluster analysis techniques as probability plot and Ward's algorithm. The calculated permeability using the 6 HFUs classification shows very good results. The determination coefficient R^2 between the calculated permeability with the HFU method and the actual permeability measured on core plugs was 0.97, indicates a nearly perfect correlation.

Applying the GHE method, the Z gas reservoirs can be divided into 7 distinct GHEs. Estimated permeability using the GHE method has a slightly smaller correlation coefficient than using the HFU method, 0.96 compared with 0.97. However, the GHE method is very useful for a reservoir with limited core plugs data and very quickly to divide reservoirs into HFUs. In fact, using this method, we can reduce the amount of core data taken from the reservoir and still provide acceptably accurate results.

Nomenclature (selected quantities)

Φ: Porosity.

Φe: Effective porosity.

Φ_z: Normalized porosity.

K: Permeability.

τ: Tortuosity.

S_{gr}: Specific surface area per unit grain.
RQI: Reservoir Quality Index.
FZI: Flow Zone Index.
GHE: Global Hydraulic Element.
HFU: Hydraulic Flow Unit.

Author contributions

The first author, Man Ha Quang, built up conception, data analysis and draft the article. The second author, Anh Le Ngoc contributed to the methodology and Jadwiga Jarzyna author give a critical review for the final version to be submitted.

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