Parity in Rock-Typing for Geology, Petrophysics, and Engineering by Tackling Interconnectivity with Fractal Leaky-Tubes Description*

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Abstract

Modified form of Kozeny-Carman equation was the basis of “hydraulic (or flow) units” methodology introduced in 1990s for rock typing. The original study proposed an algebraic manipulation of the equation to derive groups of similarities in porosity-permeability relations. The attempt was for managing the statistical non-representative nature of limited number of samples in a given study, by assuming similar capillary bundles would govern fluid flow in a similar manner. In this study, capillary-bundle approximation is replaced with leaky-tube hydraulics that is bounded by pigeonhole fractal model of pore space. By addressing interconnectivity of flow-paths through leaky-tube hydraulics and using fractal dimensions for identifying similarities, the shortcomings of capillary-bundle assumption is inhibited; making the revised rock-typing a common-denominator between petrophysics, engineering and geology. The original “hydraulic units” approach was devised for sample selection for core analysis providing better coverage of the spectrum of rock properties; hence, the simplification of porosity-permeability relation did not affect the outcome. However, the methodology was extended by practitioners into modeling and prediction of rock properties that were fed into static models with a non-trivial failure rate throughout the years. Although, the methodology served as a great simplifier of data management and manipulation, the capillary bundle assumption has been the culprit of the failure of modeling and prediction of rock properties for heterogeneous rocks that violate the very assumption of capillary bundles. In this study, more progressive modification of original methodology for rock typing is proposed to circumvent the shortcomings of basic assumptions in Kozeny-Carman relation of pore space and flow- controls. The modifications require additional Wireline

data that are becoming standard logging suites of today. The sought-after agreement in rock typing between disciplines and proper modelling and propagation of rock properties for a field, justify the incremental cost of required data for pivotal wells in a field.

Introduction

The concept of rock-typing in terms of “hydraulic (flow) units”1 (HU) in petroleum reservoirs was introduced by Amaefule et al. (1993), who rearranged the Kozeny-Carman (KC) equation (Kozeny, 1927; Carman, 1937) in order to identify groups of similarities in core-derived porosity-permeability relationships. This was done by introducing the concept of a “flow zone indicator” (FZI) as a characterizing parameter. That approach provided a means of managing the uncertainties in rock property distributions given that core analysis might be statistically unrepresentative of a porous medium. The underpinning assumption was one of fluid flow through “groups of capillary bundles of tubes”. The capillary tubes are isolated hydraulically from each other and, in this respect, they only partially represent the nature of flow through porous media.

Methods

The HU approach was intended to improve sample selection for core analysis by allowing a greater insight into the variation of rock properties in petroleum reservoirs. However, since it was introduced, the methodology has been extended by practitioners to the numerical modelling of rock properties, and sometimes this has resulted in a significant shortfall in predictive capability, especially with regard to permeability. Thus, although the HU methodology did indeed enhance data management and analysis, the assumption of bundles of isolated capillaries as per KC has precluded the meaningful extension of the method for the modelling and prediction of reservoir properties for heterogeneous rocks that evidently do not satisfy that precondition. These observations have led the authors to consider an extended model whereby the tubes are interconnected and therefore are more representative of flow through porous media.

To achieve this, the capillary-bundle of tubes approximation of the KC equation is integrated with a leakytube hydraulic approach (Civan, 2002a) that is further controlled by a pigeonhole (Pape et al., 1987) fractal model of pore space to represent the heterogeneous character of petroleum reservoirs. By allowing interconnectivity and consequential cross-flow in this way, the earlier shortcomings of the capillary-tube model can be overcome to a significant degree. This, in turn, leads to an enhanced rock typing with fractal dimensions being used to observe similarities. In this way, the method forms a common basis for the various methodologies applied in geoscience, petrophysics and reservoir engineering.

The key equation of the "HU" approach was:

$$\log(RQI) = \log(FZI) + \log(\phi_n) \tag{1}$$

where RQI = $(k/\varphi_e)^{0.5}$, $\varphi_n = [\varphi_e/(1 - \varphi_e)]$, FZI= $1/((Fs)^{0.5}\ \tau\ S_{gv})$, or simply, FZI=RQI/$\varphi_n$, k is absolute permeability, and φ_e is effective porosity. Both permeability and porosity are conditioned by the capillary tube model.

Discussion

The leaky-tube model that is the basis for our study described by the following modified form of equation (1):

$$\log\left(\sqrt{\frac{k}{\phi_e}}\right) = \log(\Gamma) + \beta \cdot \log\left[\frac{\phi_e}{\alpha - \phi_e}\right] \tag{2}$$

where Γ is an interconnectivity parameter (Civan, 2002a,b), α is a pore volume reduction factor that takes account of phenomena such as cementation, and β is a fractal dimensional parameter (Civan, 2003) that accommodates leakiness and is defined as:

$$\beta = \left(\frac{3 - D}{3}\right) \cdot \left(\frac{d}{d - D}\right) \tag{3}$$

where D is the fractal dimension of pore surface area to bulk volume and d is the fractal dimension of pore surface area to pore volume. The fractal dimension "D" is a pigeonhole function of average tortuosity (Pape et al, 1998) τ_{av}, effective pore radius r_{eff} and average grain radius r_g, and the fractal dimension "d" is a function of porosity and permeability. In equation (2), β is obtained from equation (3), the interconnectivity parameter can be obtained graphically by Civan (2002a,b; 2003), and the pore reduction factor α can be estimated through Wireline log data and pore image analysis. Note that adoption of equations 1, 2 and 3 does not exclusively relate to fluid flow. It has also allowed the representation of no-flow conditions at a percolation threshold where the connected pore-throat sizes become less than the critical size required for fluid flow. This is a major advantage of the present approach.

The fractal leaky-tube model has been applied to a variety of reservoir situations. Two examples are illustrated in Case 1 and Case 2. The main objective of this study is to demonstrate that the extension of the notion of “flow through capillary bundles” to “flow-through leaky-capillary bundles” creates a better common denominator between the geologically (FG) and petrophysically driven rock types (EHU).

Case 1

Conventionally generated hydraulic units (HU) and extended hydraulic units (EHU) plots for this case are shown in Figure 1. The comparisons of the geologically identified rock types (FG) with HU and EHU are given in Figure 2.

Case 2

Conventionally generated hydraulic units (HU) and extended hydraulic units (EHU) plots for this case are shown in Figure 3. The comparisons of the geologically identified rock types (FG) with HU and EHU are given in Figure 4. Special Core Analysis (SCAL) data have also been compared as a function of three different methods of rock typing for four different rock types for Case 2 data. These are shown in Figure 5.

Conclusions

Extended HU methodology (EHU) for rock typing uses hydraulics of leaky-capillary-bundles together with fractal dimensions of pore-space as a basis for similarity criteria. The integration of the fractal character of a pore system leads to a modified KC equation that allows a more accurate representation of flow through such a porous medium. The proposed model of pore structure is independent of prevailing fractal dimensions. In particular, no-flow conditions are reached at a percolation threshold where the connected pore-throat sizes are less than the critical size that allows fluids to flow. This aspect renders the EHU methodology more accurate and responsive to those reservoir attributes that contribute to geological rock typing. Furthermore, with the proposed methodology, equivalence between geological, engineering and petrophysical rock typing has become more readily attainable, and this outcome should lead to improved building blocks for both static and dynamic reservoir models.

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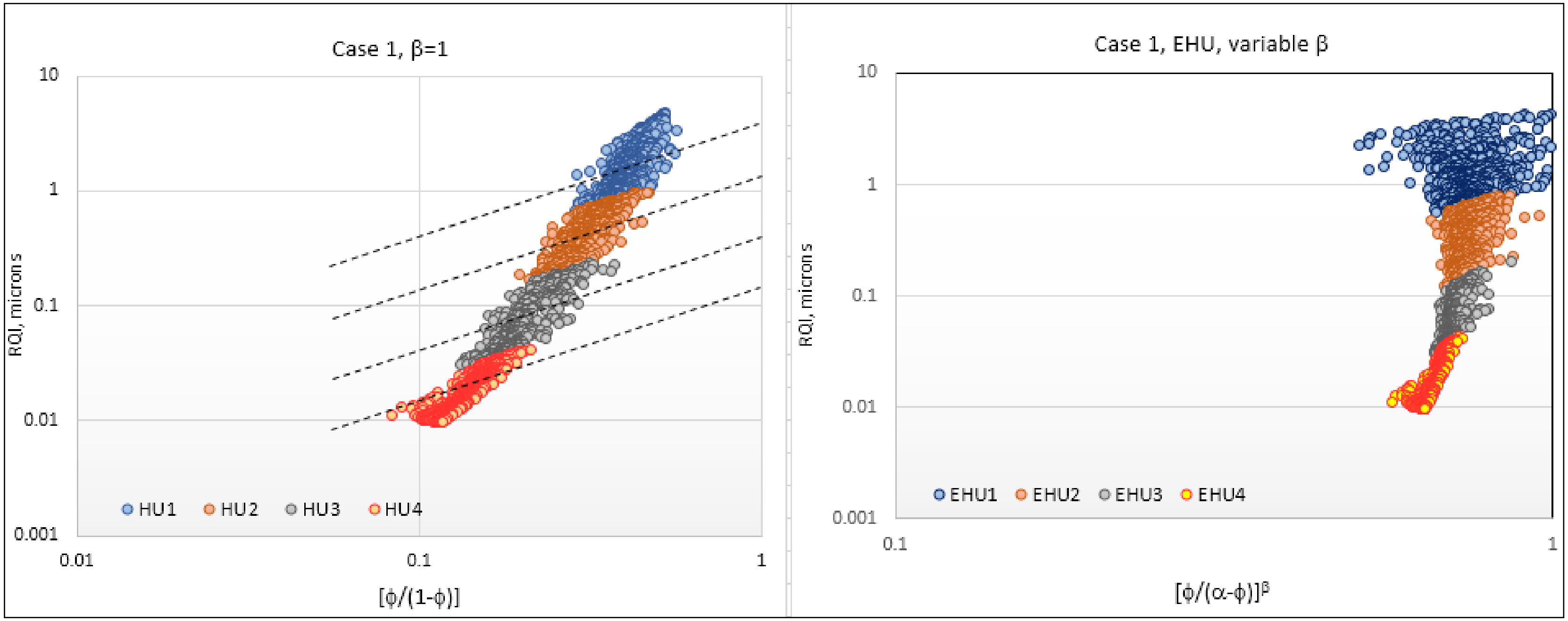

Figure 1. Bilogarithmic crossplots for Case 2. Due to removal of the requirement of unit gradient as a basis for grouping, the EHUs have been identified without such a restriction.

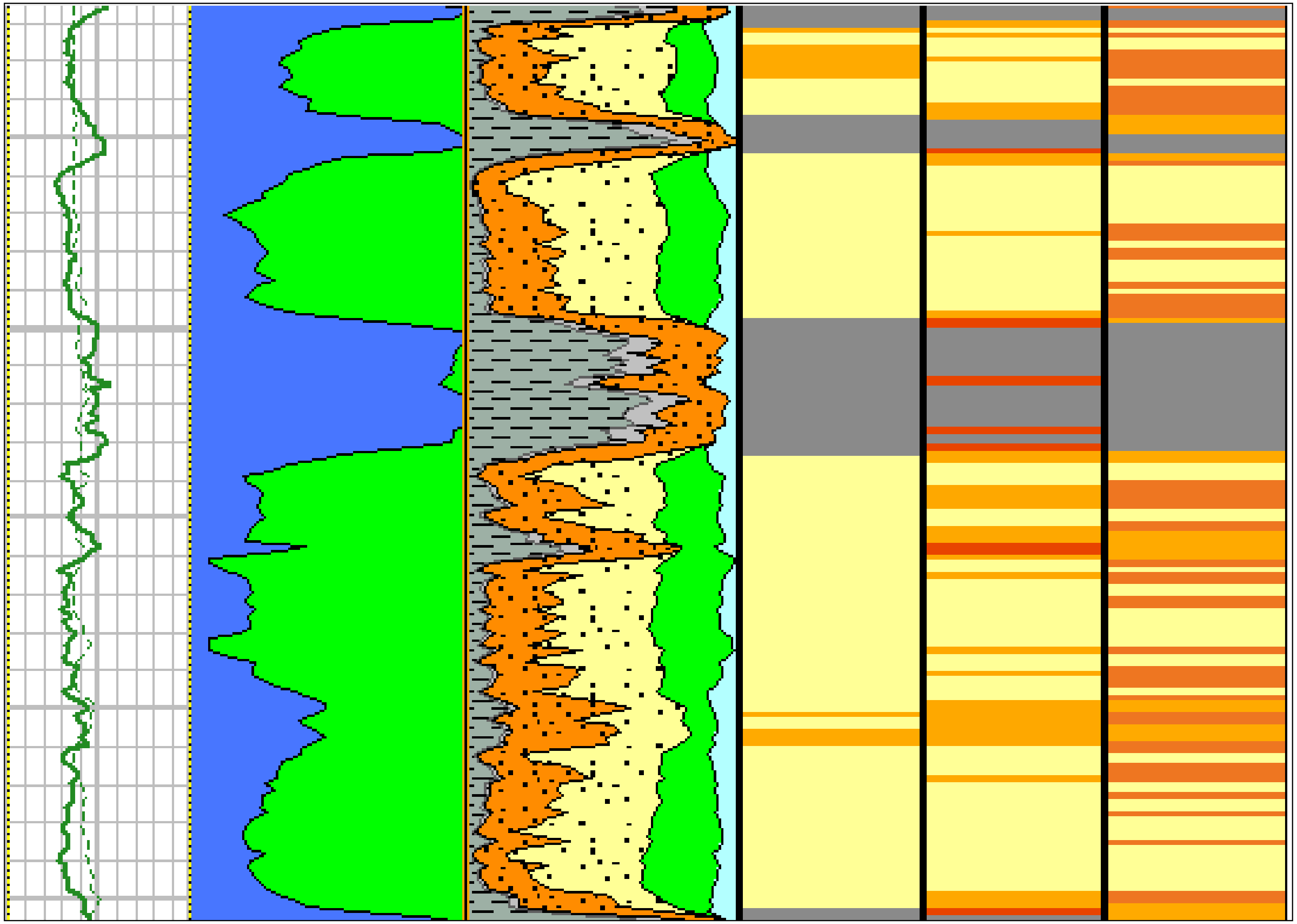

Figure 2. Tracks from left to right show GR, Sw, Volumetrics, geologically driven rock types (FG), EHU, HU. There is more evident similarity between FG and EHU than between FG and HU.

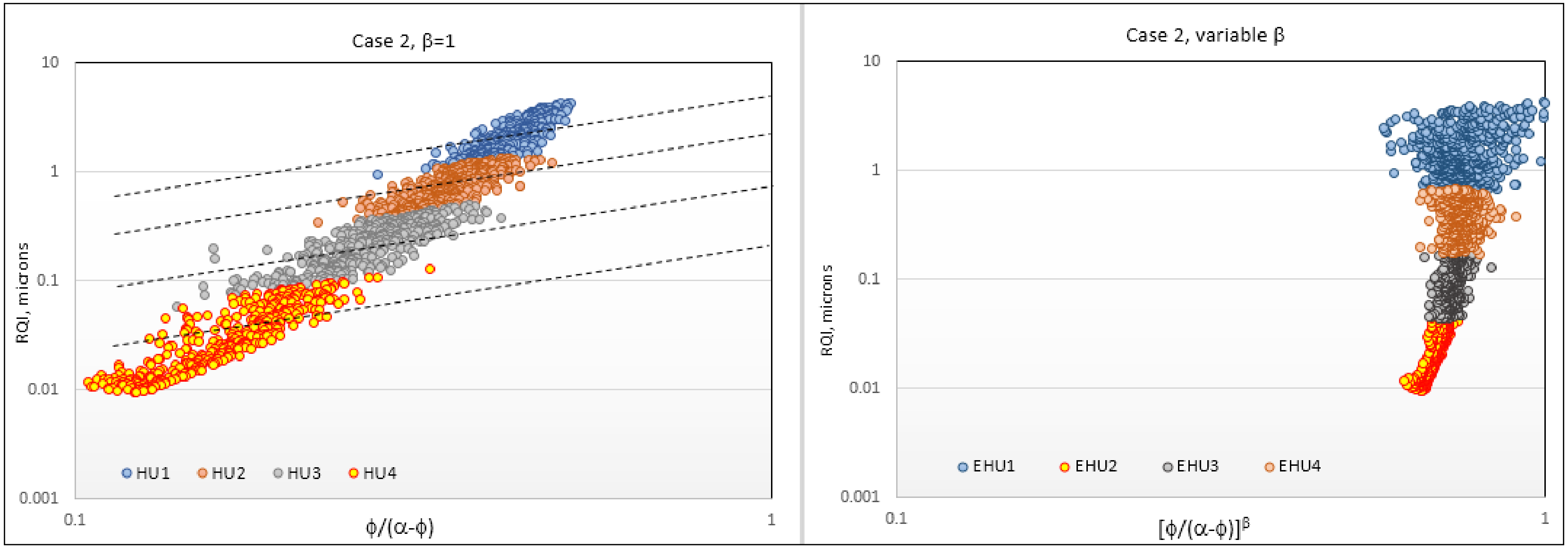

Figure 3. Bilogarithmic crossplots for Case 2. Due to removal of the requirement of unit gradient as a basis for grouping, the EHUs have been identified without such a restriction.

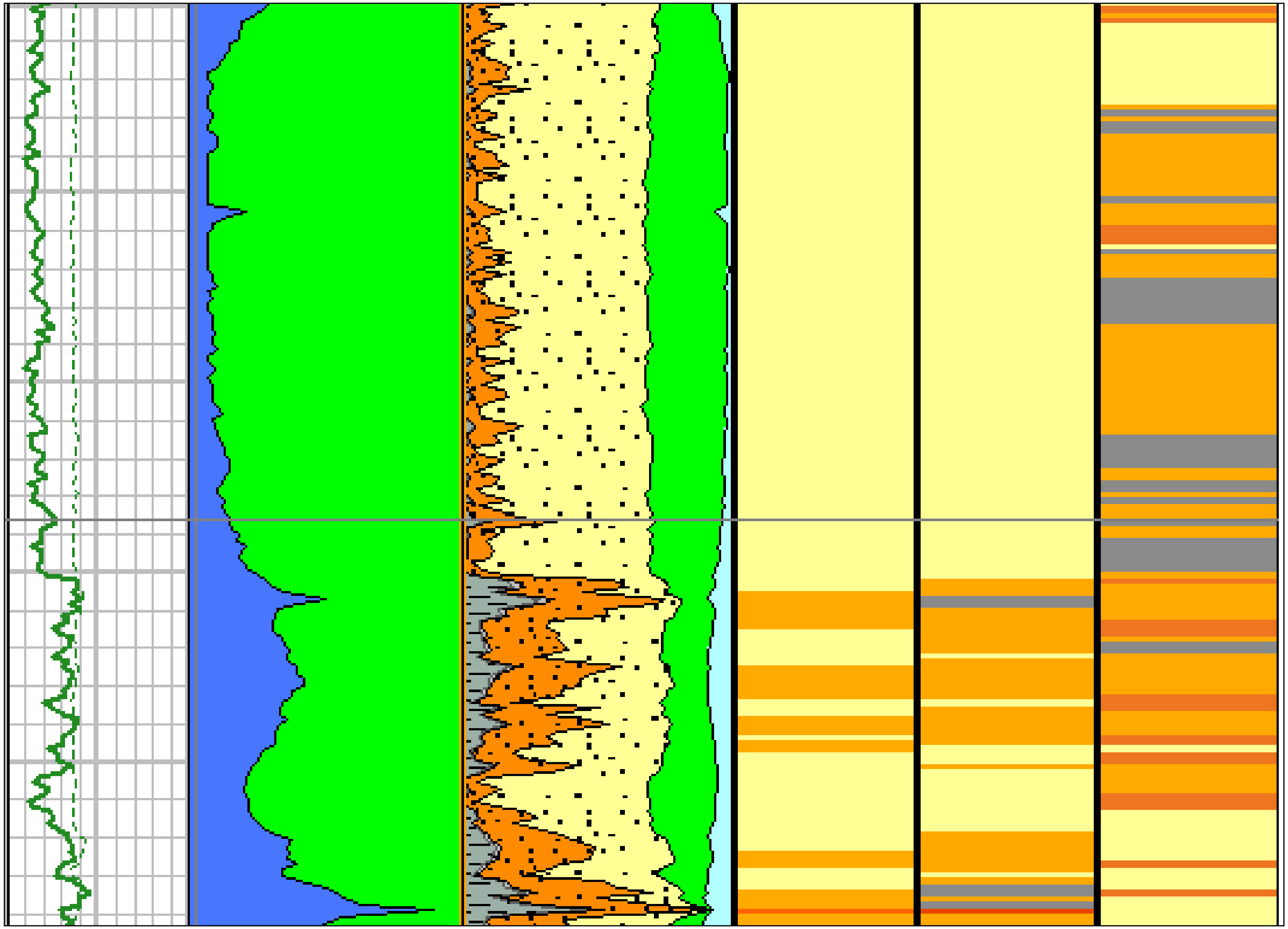

Figure 4. Tracks from left to right show GR, Sw, Volumetrics, geologically driven rock types (FG), EHU, HU. There is more evident similarity between FG and EHU than between FG and HU.

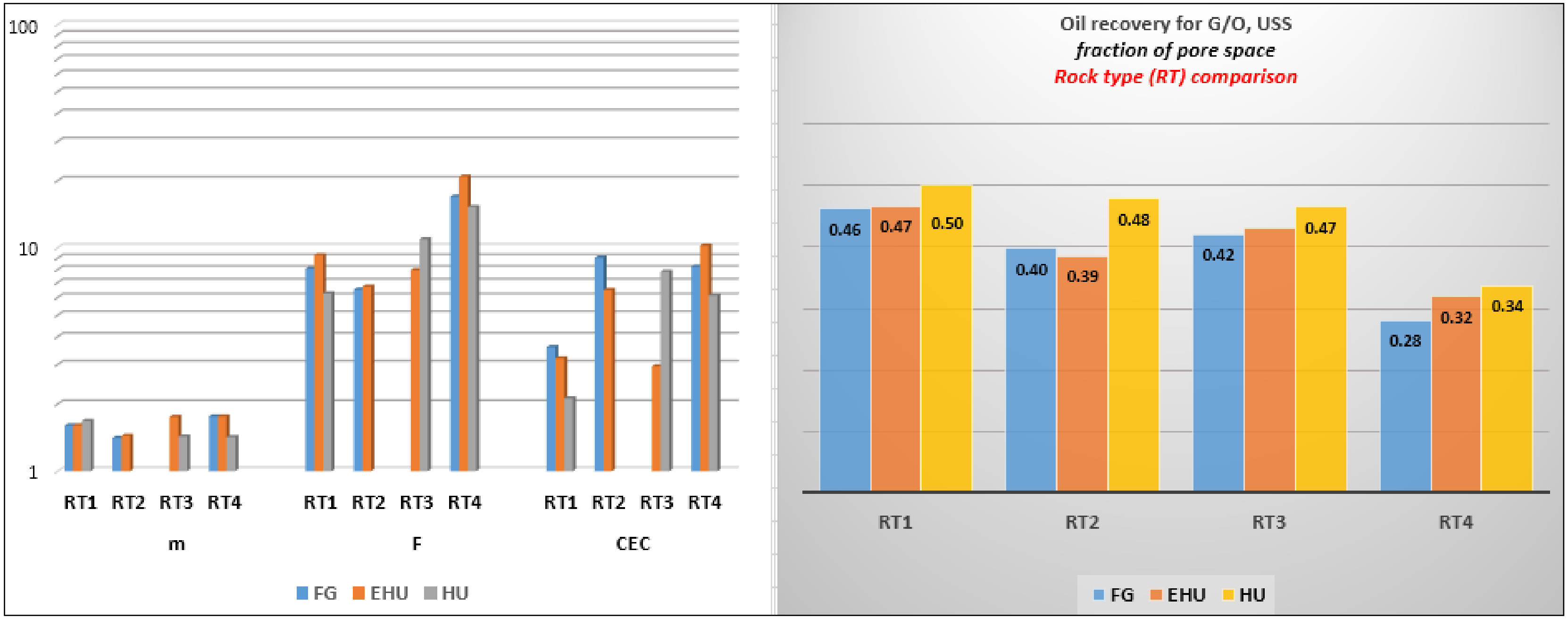

Figure 5. SCAL data demonstrate that the similarity between petrophysical properties of rock types is broadly stronger for the FG and EHU methodologies than it is for the FG and EHU methodologies (m is the porosity exponent as per Archie (1942), F is the formation resistivity factor, and CEC is cation exchange capacity.)