PETROPHYSICAL CHARACTERISATION IN GEOTHERMAL RESERVOIRS: WHAT FOR?

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ABSTRACT

The rocks found in geothermal systems are widely heterogeneous and complex, yet they need to be represented numerically so that the features of the system can be modelled and the system's behaviour simulated to achieve optimal field management.

Geological parameters conventionally used to classify rocks for geological models, e.g., lithology or origin, seldom provide numerical data related to their physical properties. These data are required as inputs for numerical reservoir models, so it is important to strengthen the petrophysical characterisation workflow so more rock-based numerical data can be provided to the models.

This paper overviews a petrophysical characterisation technique based on textural features and presents it as a tool for the geothermal fields of New Zealand. We show how this technique may be used to estimate petrophysical values of reservoir and seal rocks based on observed features by using examples of rock types from the Tauhara Geothermal Field of New Zealand.

1. INTRODUCTION: ADDING SOME COMPLEXITY

Experience in volcanic petroleum reservoirs indicates that reservoir management may be improved by increasing the detail of computer models to reflect the complex geology (e.g., Chowdhury et al., 2014; Li, Zhao, & Han, 2014). This can be done with the appropriate integration of petrophysical parameters needed for the numerical models, including hydraulic (e.g. porosity and permeability) and thermal (e.g. thermal conductivity) characteristics. Although these properties might be available from drill-core samples or electrical logs, the upscaling of these values to fit in the numerical models remains poorly studied. If these measurements are not available, they need to be assumed as constant or calibrated through manual iteration or computer assistance (Kaya, O'Sullivan, & Hochstein, 2014; Kaya, O'Sullivan, & Yeh, 2014).

The main objective of petrophysical characterization is to translate geological information, especially hydraulic and thermal properties, into quantitative values for numerical models. Conventionally in petroleum reservoirs, the data from drill-cores, electric logs, seismic surveys and any other source available are analysed and integrated. Then, these properties are interpolated using geostatistics to build a three-dimensional model that can be used in the numerical model. When there are abundant data available they normally need to be simplified or upscaled to accommodate the resolution of the numerical modelling grid.

In some geothermal fields, there is not enough data available to populate a petrophysical model. It is then ideal to start big and go smaller. A common starting point is by using stratigraphic units. However, geothermal rocks are complex as they are subject to formational and diagenetical processes that change their primary properties (Sruoga & Rubinstein, 2007). This means, conventional indexing by geological formations, composition, or chronostratigraphy, does not give appropriate petrophysical information for a numerical model.

One alternative is to use rock chips or drill-cuttings as a source of petrophysical information. These are the most abundant samples available in geothermal fields, and have the potential to provide enough detail to populate a petrophysical model. This means, starting small and then scaling up to reservoir dimensions. As a result, more complexity of the rocks can be integrated and more realistic scenarios are considered, ideally leading to less time calibrating these properties in the numerical models. If the models do not respond to the rock properties, then other setups (like dual permeability) are to be considered.

2. THE GOLDEN RULE: KEEP IT SIMPLE – A TEXTURAL APPROACH

The use of rock chips has been proven useful in petroleum reservoirs. By observing certain textural features in drill-cuttings, a petrophysical model can be created following a petrophysical classification. As reference, the petrophysical classifications of Archie (1952) and Lucia (1995) for carbonates and of Sneider et al. (1983) for sandstones have been considered. Archie classified rocks based on surface appearance, particle size and pores size. Lucia used pore types, rock fabric, and particle size in his classification. Sneider used consolidation, pore volume and pore type. Sneider (2010) presented an integrated more recent application of these textural features. He uses particle size, sorting, groundmass content and pore volume for sandstones; and composition, rock fabric, pore volume and pore type for carbonates.

Several of these features are commonly described in the petrography of igneous rocks, e.g., particle size, while others are not commonly used, e.g., surface appearance. None of these features have been used for petrophysical characterisation of coherent lavas and volcaniclastic rocks in geothermal reservoirs. Therefore, the first step was to redefine, adjust and apply these features in the context of volcanic rocks (Prieto & Archer, 2015; Prieto, Mielke, Archer, Sneider, & Misra, 2014). It was observed that only some of these features display a correlation with porosity and permeability in the studied igneous rocks. Therefore, it was not appropriate to use the existing petrophysical classifications and a different scheme was proposed to incorporate only relevant features.

3 THE RECIPE: START WITH WHAT YOU HAVE

Drill-cuttings are the most common sample type in geothermal fields of New Zealand. Frequently they are not big enough to be measured with standard procedures in a laboratory as core samples can be. In the Tauhara geothermal field a set of core samples was collected for geotechnical purposes. This provided a good dataset of 190 core samples with measured properties (Mielke, Bignall, & Sass, 2010; Nehler, 2012) and allowed us to simulated rock chips to observe their textures (see Prieto et al. (2014) for details on sample preparation).

Our work has focused on 12 textural features or descriptors and their relationships with porosity and permeability (see Prieto et al. (2014) for definitions and description methods). We started with the descriptors used for carbonates and sandstones: surface appearance (SA), rock fabric (RF), particle size (PS), sorting (SO), groundmass content (GMC), pores size (PORS), pore types (PT), pore volume (PV), consolidation (CO). Later on, nature (PFM), source (PFS) and occurrence (PFO) of the pore-filling materials were added (Prieto & Archer, 2016). A correlation between these descriptors and permeability and porosity has been observed for rock fabric, groundmass content, consolidation, pore volume, pore size, pore type and occurrence of pore-filling material (Figure 1). However, as other petrophysical classifications show, a single descriptor is not enough to assess the pore geometry of a rock.

4. CLUSTERING: THE ROAD TO ROCK TYPING

To take advantage of the powerful capacity of neural networks to detect unknown patterns and clusters within big datasets, the authors used these descriptors as inputs in Self-Organising Maps (SOMs) (see Prieto & Archer (2015) for details of networks set up).

Prieto & Archer (2016) reported on three combinations of descriptors RT1: RF, GMC, CO, PV, PORS, PT, PFO; RT2: GMC, CO, PORS, PT, PFO; and RT3: GMC, CO, PT, PFO. Three fussy clusters were observed when using seven descriptors together (RT1). This result is similar to the three clusters reported previously in Prieto & Archer (2015). It is observed in the weight planes plot for RT1 (Figure 2) that the uniform orange-reddish colours across the neurons provide no differentiation of clusters for inputs 1 (RF) and 4 (PV). This is interpreted as both inputs not having relevant weights in the clustering process; therefore they were excluded for the combination RT2. It was also observed that inputs 3 and 5 (CO and PORS) show a correlation in their patterns. We interpret this as both descriptors affecting the clustering in the same way, thus we only used consolidation for RT3. Consolidation is a featured that is easier to describe.

When using RT2 and RT3, four clusters distributed in different regions of an effective porosity vs. air permeability cross-plot (Figures 3a and 3b, respectively) were observed, with better definition for RT3 (Figure 3b).

We have compared the standard distance deviation of each cluster within RT2 and RT3, using porosity and the logarithm of permeability (Table 1). The standard distance deviation is a two-dimensional measure of a cluster dispersion given by Equation 1. Having considered our previous observations of three clusters, we also compared the deviation of RT3 with three clusters. The one with combined lower dispersion is considered the more appropriate one, hence, we decided on a combination of groundmass content, consolidation, pore type and pore filling occurrence, with three classes defined by the three clusters (Figure 3c).

Table 1: Standard distance deviation of clusters for combinations RT2 and RT3.

	RT2	RT3-4 clusters	RT3-3 clusters
Cl1	7.8	10.22	10.22
Cl2	10.06	9.90	10.60
Cl3	9.94	12.69	12.71
Cl4	9.78	11.39	-

Equation 1 $$S_{xy} = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{X})^2}{n} + \frac{\sum_{i=1}^{n}(y_i-\bar{Y})^2}{n}},$$

where x_i and y_i are coordinates, and $\bar{X}$ and $\bar{Y}$ are the cluster mean centre in *x* and *y* coordinates.

5. ROCK TYPES AT WORK

Using a numbering scheme produced when combining the descriptors' digits (Figure 4), we generated rock types for two wellbores (Figure 5). A number identifies each sample analysed (column 1), and two samples with the same number are considered as belonging to the same rock type (column 2).

These rock types, may have a good correlation with lithology (in column 6), but they are not expected to match it precisely. This is because lithology may have a genetic as well as a textural connotation and because not only formational but also diagenetical and tectonical processes are included in the observation of the textural descriptors used. For example, different lithologies may/can display the same textural features, e.g., a lutaceous rock in the Lower Huka Falls Formation and a pyroclastic rock in the Waiora Formation, both belong to rock type 2431. In the same way, the same lithology displays different descriptors, e.g., lava flow-2531, lava flow-3632.

A correlation between these rock types and measured porosity (column 4) and permeability (column 5) is observed. In this sense, the rock types offer a high degree of detail and a good proxy to permeability and porosity independent of the lithological unit. On the other hand, this degree of detail is not practical at reservoir scale.

As previously observed, several rock types can be grouped and simplified into three clusters according to their porosity/permeability ratio (column 3), and still offer a higher degree of detail compared to the stratigraphic units in column 7. These upscaled rock types are displayed as a background in columns 4 and 5 showing a good correlation with the measured petrophysical properties. We will refer to these clusters as petrophysical rock types or petrotypes.

6. THE NEXT STEP: PREDICTIONS

The relationship between petrotypes and porosity and permeability can be used as a prediction tool. Measuring permeability requires especial equipment, but measuring porosity is a common practice of the rig geology services.

Every rock type belongs to one of three petrotypes in the studied samples. Examples are shown in Table 2.

Envelope lines for our dataset are shown as black dotted lines with respective equations as example in Figure 6. Trendlines for each petrotype are shown in dark red lines. The ultimate goal is to provide values of permeability for modelling purposes. If porosity values were available, then permeability could be estimated from given equations.

Table 2: Example of rock types and corresponding petrotypes.

Petrotype 1	1431,1531,2521,3211,3232,3411,3421,3431
Petrotype 2	1311,1321,1322,1411,1421,1422,1521,1522
Petrotype 3	1432,1532,1632,2331,2531,2431,2432,2632

Future work is still to be done on these equations. Due to the data dispersion, a permeability value can vary up to two orders of magnitude, so we need to analyse the relevance of the outliers for each cluster. If the data dispersion is not an artifact, then a probabilistic approach to populate a petrophysical model could be considered in which the envelope values are taken as P10 and P90, and the trendlines as P50. In this case, the numerical modeller could initialize the model with three values with some certainty.

In addition, with a catalogue of rocks like the one we aim to produce, an analyser can visually compare the rock samples available. If a match is found, the analyser can assign with some certainty a rock type number to the samples and even a set of measured petrophysical values. Once the petrophysical model is created and used for simulation, the system's structural details can be included to consider more complex setups like dual permeability as needed.

This rock classification based on hydraulic properties could be tested for thermal properties to determine if there is any potential application.

7. CONCLUSIONS

The detail of computer models may be increased to reflect the complex geology of geothermal systems by integrating petrophysical models. However, the input of these models depends on the available information and it is known that conventional indexed geological units do not give appropriate petrophysical information for a numerical model.

Drill-cuttings are the most abundant samples available in geothermal fields, and they have the potential to provide enough detailed information to populate a petrophysical model by using certain textural descriptors observable on hand samples without sophisticated tools.

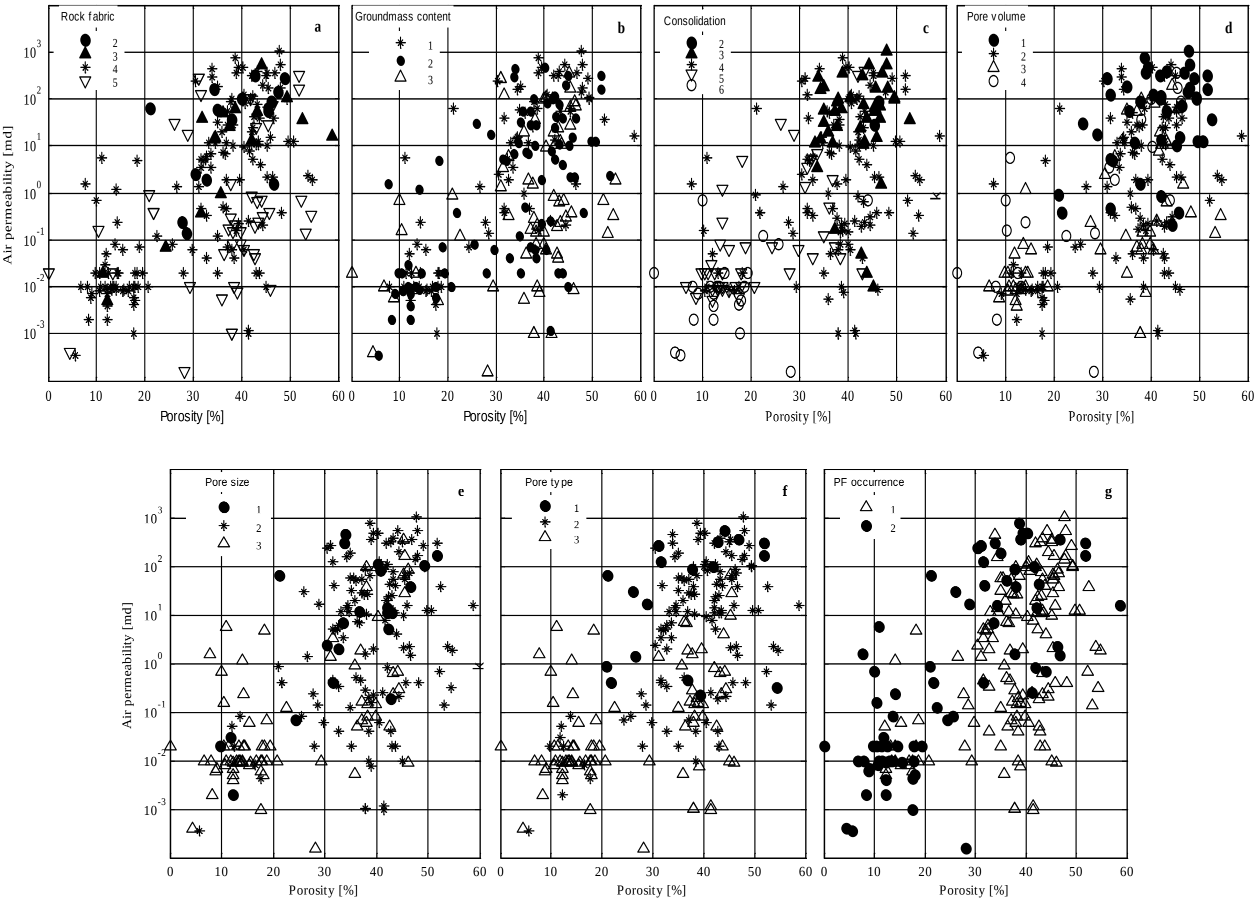

Figure 1: Effective porosity vs. air permeability cross plots comparing classes of selected textural descriptors (a) RF; (b) GMC; (c) CO; (d) PV; (e) PORS; (f) PT; (g) PFO (Prieto and Archer, 2016).

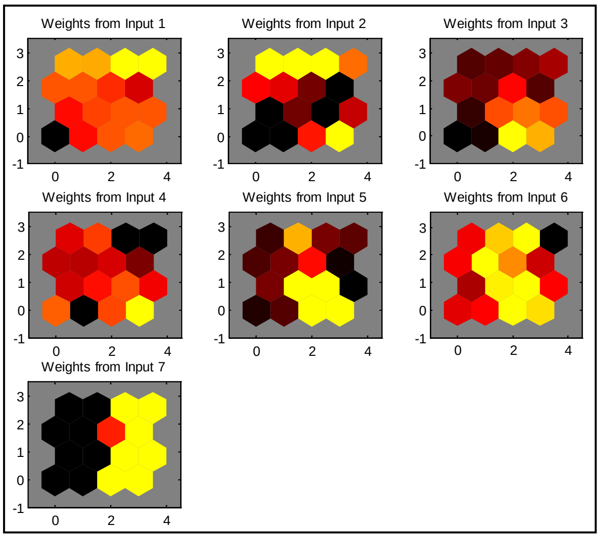

Figure 2: Graphical representations of a SOM. Weight planes plot for the numbering scheme RT1, featuring descriptors: RF, GMC, CO, PV, PORS, PT, PFO (Prieto and Archer, 2016).

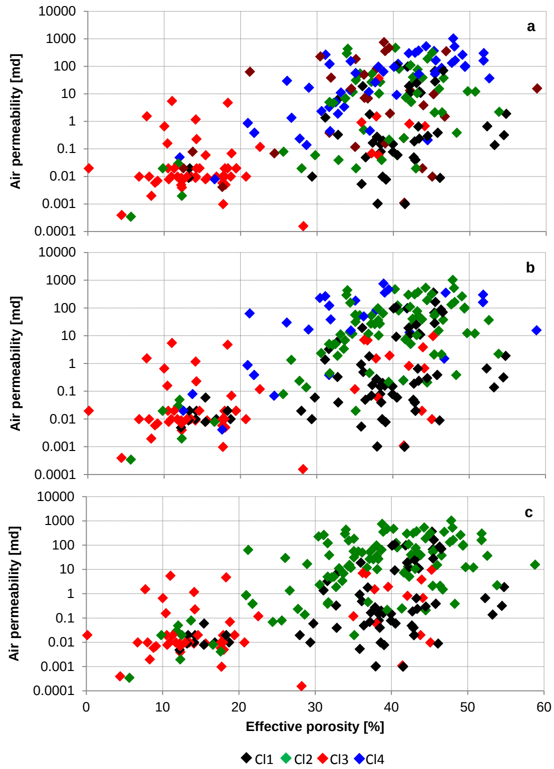

Figure 3: Effective porosity vs. air permeability cross-plots with indexed samples divided in clusters (Cl1, Cl2, Cl3, Cl4) for combinations (a) RT2: GMC, CO, PORS, PT, PFO, and (b) and (c) RT3: GMS, CO, PT, PFO.

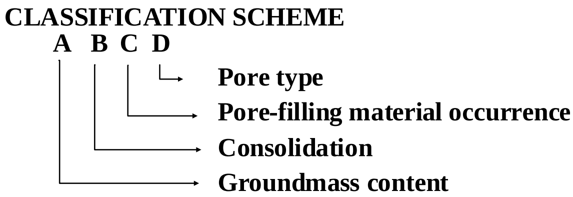

Figure 4: Classification scheme proposed for rock typing.

The descriptors used in the petrophysical classifications of clastic and carbonate reservoirs are not necessarily relevant for volcaniclastic and effusive rocks. A different scheme is proposed using groundmass content, consolidation, pore type and pore-filling occurrence.

Using these descriptors the samples can be classified into rock types. These rock types do not correspond precisely to lithological or stratigraphic units, but have a correlation with porosity and permeability. Rock types can be grouped into petrotypes that have similar petrophysical properties and are appropriate at a reservoir scale for modelling.

Petrotypes and the equations describing their values of porosity and permeability can be used as a prediction tool. Once rocks are classified in petrotypes, if porosity values are available then permeability can be estimated. Also, a catalogue of petrotypes with visual comparators can provide measured petrophysical properties for matching rocks. Future work is to be done to refine, test and validate the equations generated for the Tauhara geothermal field dataset, and to build its rock catalogue.

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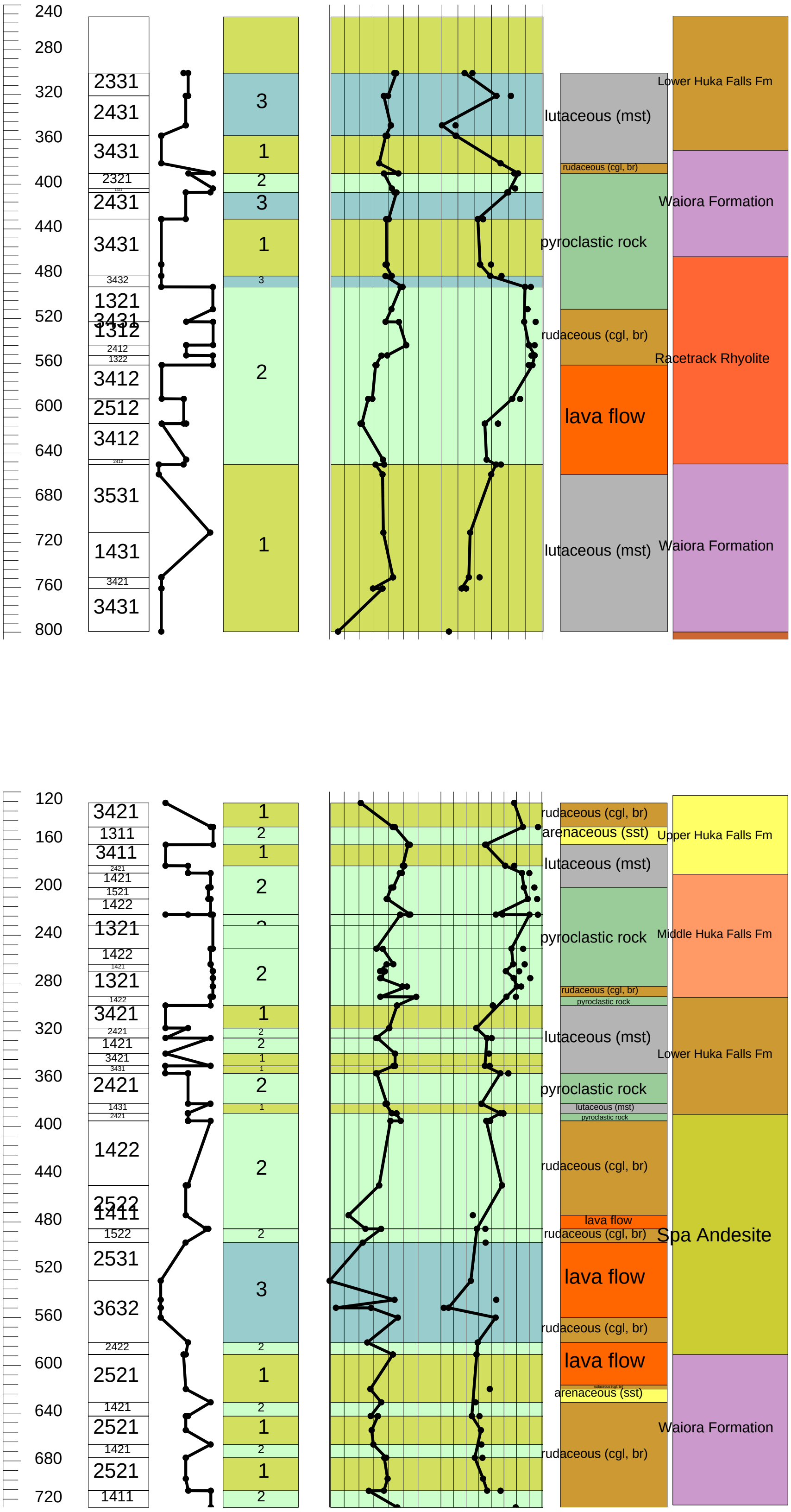

Figure 5: Rock typing examples in two wellbores. Rock types (columns 1 and 2) and petrotypes (column 3) correlated with measured effective porosity-phi- (column 4), air permeability (column 5), lithology (column 6) and stratigraphic units (column 7).

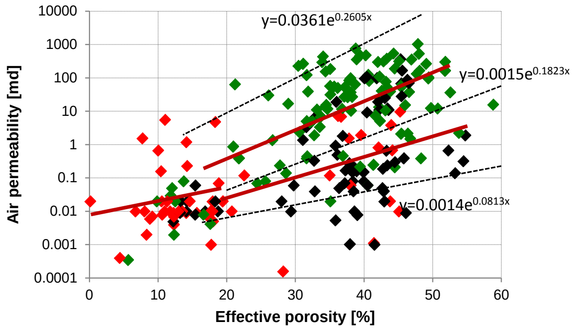

Figure 6: Petrotype envelopes (dotted black lines) and trend lines (dark red lines).

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