Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Permeability and Porosity Estimation Using Textural Descriptors

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Keywords: descriptors, petrotypes, petrophysical characterization, permeability, porosity, geothermal reservoirs, reservoir geology, Tauhara, New Zealand,

ABSTRACT

Porosity and permeability are critical petrophysical properties for reservoir modelling, as they represent the reservoir's ability to store and transmit fluids. These properties can be collected directly from tests on rock samples, interpreted from electrical logs or borehole tests, or calibrated by computer models. Two main features are desired from these properties, that they are a good representation of the actual geology and that they can be used at a scale suitable for computer modelling. Geothermal settings can hinder the collection of petrophysical data. The costs of operation of collecting samples, the response of the geophysical tools, and the satisfactory operation of equipment in hot environments, are examples.

Alternative methods to source these properties are essential when the data is not feasible or possible to collect. A characterization method using textural descriptors to generate petrophysical rock types, or petrotypes, has been developed for volcanic and volcaniclastic rocks. Four descriptors observed on hand samples, consolidation, groundmass content, pore type, and pore-filling occurrence, are combined to classify rocks into petrotypes. Three main petrotypes were identified with ranges of porosity and permeability that could be applied for properties population with a probabilistic approach. Rocks with a similar combination of descriptors can be used as analogues in cases where petrophysical data is scarce but hand samples are available.

This paper presents the application of petrotypes in the Huka Group of the Tauhara Geothermal Field in New Zealand. Descriptors were observed at different depths on samples from four wellbores. Rock samples were classified into petrotypes according to their descriptors, and petrotypes were interpolated in the studied depth intervals. Cross-sections between the wellbores are shown with the interpolation of petrotypes in 2-dimensions. This approach shows petrotypes derived from textural descriptors working as a source of porosity and permeability estimates and as an upscaling tool that makes spot petrophysical measurements more appropriate for reservoir simulation.

1. INTRODUCTION

Geothermal energy in New Zealand is currently contributing to 17% of the national electricity production (Ministry of Business Innovation & Employment, 2018). Over 60 years of experience has led the country into knowing about exploration, development, and use of its geothermal resources. Countries have started walking the same path with 500 MW added per year to the geothermal capacity generation in the last 5 years, mainly from emerging economies with untapped resource available (IEA, 2019).

1.1 Sourcing Petrophysical Properties

Creating numerical models of geothermal systems presents various challenges. One of those challenges is that the modeler needs to provide the simulator with numerical values that represent the physical behavior of the rocks related to how the fluids flow or how they transfer heat. These values are given by physical properties such as porosity, permeability, density, thermal conductivity, and heat capacity. Sourcing these petrophysical properties is a relevant part of the modeling workflow.

Petrophysical properties are sourced differently at different stages of development of a geothermal system. At early stages, the superficial observations are the key to what lies underneath. Using petrophysical properties from analogue rocks sourced from equivalent geological locations aids in assigning estimated values at depth. Once the drilling commences in exploratory wells, petrophysical values can be measured by collecting cores that are sent to the laboratory for testing. These samples provide spot measurements at a certain depth and need to be upscaled to represent the reservoir. Often, a representative number of core samples are needed which is costly for the project, however core acquisition is invaluable in terms of the data and understanding of the reservoir. Additionally or alternatively, using wireline logging provides continuous data in depth. Some properties can be measured, e.g., porosity, some others need to be estimated, e.g., permeability. Wireline logging is costly and can be technically challenging due to the high temperature, however, it is invaluable as well. During testing appraisal, production, or injection wells, productivity and injectivity indexes are measured to provide an estimate of how the wellbore performs. These tests provide estimated values of properties, such as transmissivity, associated to all the reservoir zones open in the borehole. Isolated tests can provide specific information about reservoirs. Well tests are performed throughout the life of a wellbore since properties in the face of the reservoir can change over time. Well testing is costly but necessary, and the technologies and operations now days are reliable.

Another source of petrophysical data has been explored using textural descriptors. A study of the application of textural descriptors in the characterization of volcaniclastic and volcanic rocks from geothermal reservoirs, has been undertaken (Prieto, 2018). The study is based on the use of descriptors in the estimation of porosity and permeability in clastic and carbonate reservoirs (e.g., Archie, 1952; Lucia, 1995; R. M. Sneider, King, Hawkes, et al., 1983) using samples of different lithologies from two geothermal fields, Tauhara in New Zealand and Salak in Indonesia. It was observed that certain textural features could describe the pore geometry of clastic and carbonates rocks and, therefore, they were related to the porosity and permeability of the rocks. The same principle was tested in rocks from the two geothermal fields to understand the applicability of this methodology. An example of how these descriptors are used to estimate porosity and permeability is presented in this paper.

1.2 Petrophysical Characterization Using Descriptors

Petrophysical characterization aims at describing a reservoir rock in terms of its petrophysical properties, their values, distribution, and spatial relationships. Petrophysical classification allows rocks to be combined into groups with similar physical properties. Features such as particle size, pores size, pore interconnectivity, and consolidation degree, are known by having a correlation with porosity and permeability, therefore they have been used to classify rocks into rock types (Table 1).

Table 1: Examples of descriptors used in petrophysical classifications for sandstones and carbonates

<table>
<tr><th colspan="4">Petrophysical classifications</th><th>Descriptors</th></tr>
<tr><td rowspan="3">Archie (1952)</td><td rowspan="2"></td><td rowspan="4"></td><td rowspan="7"></td><td>Rock surface appearance</td></tr>
<tr><td>Pore size</td></tr>
<tr><td rowspan="3">Lucia (1995)</td><td>Grain and crystal size *</td></tr>
<tr><td rowspan="7"></td><td>Rock fabric +</td></tr>
<tr><td rowspan="3">Sneider et al. (1983)</td><td>Pore types +</td></tr>
<tr><td rowspan="5"></td><td>Consolidation degree</td></tr>
<tr><td>Pore volume *+</td></tr>
<tr><td rowspan="3"></td><td rowspan="3">Sneider (2010)* Sst +Ls/Dol</td><td>Matrix content*</td></tr>
<tr><td>Sorting (SO)*</td></tr>
<tr><td>Composition+</td></tr>
</table>

Nine descriptors from sandstones and carbonates were initially considered to investigate the applicability of this method to volcanic and volcaniclastic rocks in geothermal settings. Their definitions and classifications were originally used as proposed by the authors. Then, these descriptors were modified to fit with the observations in the studied rocks as needed, for example, proposing different classification intervals (e.g., Prieto & Archer, 2015). Three more descriptors were added to include features common to hydrothermally altered rocks (Table 2). These twelve textural features were analyzed individually and in combination and it was confirmed that, in these lithologies, some descriptors also display stronger relationship with porosity and permeability. Details of the definitions, observation methods, and classification can be found in Prieto (2018).

Four descriptors were selected to propose a rock typing system applicable to volcanic and volcaniclastic rocks, these are consolidation degree, pore type, groundmass content, and pore-filling material occurrence (Table 2). These traits were found 1) to correlate to other descriptors serving as proxies for them, 2) to be simple to observed on hand specimens with hand lens or under the microscope, and 3) to change accordingly to porosity and permeability variations.

Table 2: List of descriptors for petrotyping in volcanic and volcaniclastic rocks

<table>
<tr><th>Adapted descriptors from sandstones (*) and carbonates (+)</th><th>Additional descriptors (Prieto and Archer, 2016)</th><th>Proposed descriptors for rock typing in volcanic and volcaniclastic rocks (Prieto and Archer, 2018)</th></tr>
<tr><td>Rock surface appearance +</td><td rowspan="9"></td><td rowspan="4"></td></tr>
<tr><td>Particle size *</td></tr>
<tr><td>Rock fabric +</td></tr>
<tr><td>Sorting *</td></tr>
<tr><td>Groundmass content *</td><td>Groundmass content (GMC)</td></tr>
<tr><td>Consolidation degree *</td><td>Consolidation degree (CO)</td></tr>
<tr><td>Pore size +</td><td></td></tr>
<tr><td>Pore types +</td><td>Pore types (PORT)</td></tr>
<tr><td>Pore volume *+</td><td rowspan="3"></td></tr>
<tr><td rowspan="3"></td><td>Pore-filling material composition</td></tr>
<tr><td>Pore-filling material source</td></tr>
<tr><td>Pore-filling material occurrence</td><td>Pore-filling material occurrence (PFO)</td></tr>
</table>

To use these descriptors for rock classification, they got combined into groups of rock types, represented by similar textural features. However, when plotted in a porosity vs. permeability cross-plot, it was observed that the rock types could be further simplified since several of them showed the same porosity and permeability trends (Figure 1a) (Prieto & Archer, 2016). This observation led to the proposal of a more general classification, referred to as petrotypes, which are three groups of different rock types that have similar porosity and permeability distribution (Figure 1b).

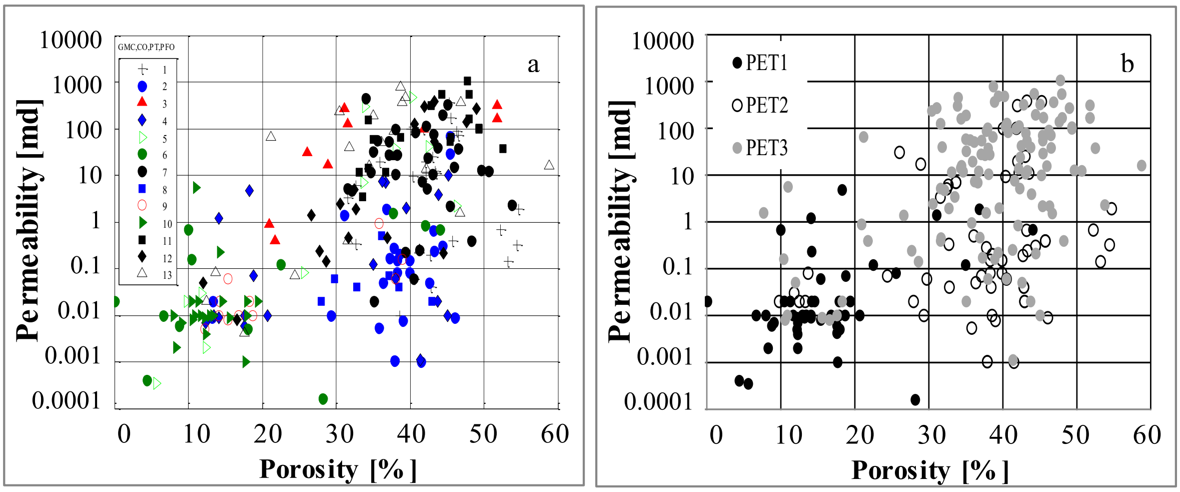

Figure 1: Effective porosity vs. permeability cross-plots of studied samples a) indexed by a combination of consolidation (CO), groundmass content (GMC), pore type (PORT) and pore-filling material occurrence (PFO) after Prieto & Archer (2016) and b) combined into petrotypes after Prieto & Archer (2018).

Petrotypes give indicative trends of petrophysical rock types, with PET1 including samples with low porosity and permeability, PET2 including higher porosity and low permeability, and PET3 including samples with higher porosity and higher permeability. Calculation of the best-fit lines for each petrotypes, and prediction intervals to limit the upper and lower boundaries of the distributions are also found in Prieto (2018).

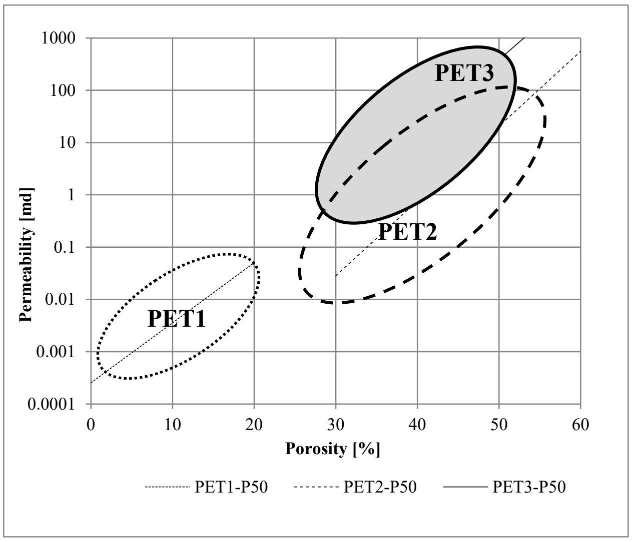

Figure 2: Effective porosity vs. permeability cross-plots showing with mean trend values (P50 lines) of petrotypes PET1, PET2, and PET3.

2. GEOLOGICAL SETTING

The formations in the Huka Group are interpreted as being associated with deposits of a paleolake, it extended throughout the Wairakei-Tauhara Geothermal System in the North Island of New Zealand (Figure 3). The Lower Huka Falls Formation (LHFF), Middle Huka Falls Formation (MHFF), and Upper Huka Falls Formation (UHFF) are the focus in this paper. Cattel's (2016) facies characterization and interpretation of this group is used as a reference and source of information. For more detail, see the original text.

The LHFF overlies the Waiora Formation with gradational to sharp contact regionally variable and the UHFF underlies the Oruanui Formation. Their age approximates between circa 190 ka and 25.4 ka, constrained by deposits of the Oruanui eruption on top.

In the studied samples, the LHFF is composed by mudstones, siltstones and sandstones, tuffs, and sedimentary breccias. The MHFF is mainly composed of tuffs and sedimentary breccias, however there are also sandstones, siltstones, mudstones, and igneous breccias. And the UHFF is formed by mudstones, siltstones and sandstones, sedimentary breccias, and tuffs. These members are 20 to 60m tick each. The lower and upper ones constitute widespread impermeable aquicludes, while the middle one is considered a shallow reservoir of hot fluids in the geothermal system.

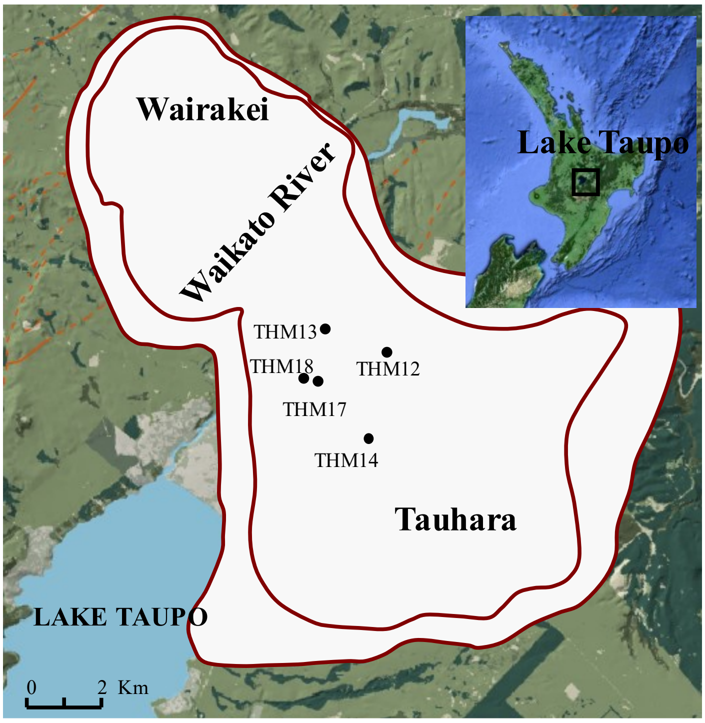

Figure 3: Location of studied wellbores in the Wairakei-Tauhara Geothermal System by the lake Taupo in the Central North Island of New Zealand. Resistivity boundary after Rosenberg, Wallin, Bannister, et al. (2010).

The LHFF reflects a lacustrine-dominated environment that was interrupted by local phreatomagmatic activity in the lake which originated the MHFF. The gradational boundary between MHFF and UHFF indicates the progressive start of lacustrine sedimentation again. The presence of coarser materials in UHFF indicates the change between lacustrine-dominated to fluvial-dominated systems.

3. METHODS

3.1 Samples

Samples from the petrophysical investigation in the TGF (Mielke, 2009; Nehler, 2012) were used for this study. 114 of them belong to the Huka Falls Formation. Drill cores of about 15 cm in diameter were taken from the nearly vertical wellbores TH18, THM12, THM13, THM14, THM17, THM18. Core plugs of 40 mm in diameter and 20 to 30 mm in length were sampled perpendicularly and along the borehole axis. End trims of 10 to 15mm thick were cut off from the core plugs.

3.2 Petrophysical Tests

The petrophysical data used was collected by Mielke et al. (2015) and Nehler (2012). Core plugs were washed with tap water and oven-dried for 48 hours at 40ºC. It was assumed this time was long enough to eliminate water. The samples were then cooled down to room temperature. Air permeability was measured using steady-state airflow in a columnar permeameter, with a 1 MPa confined Hassler-cell set at five pressure stages from 1,080 kPa to 5,000 kPa.

Bulk density (ρ_g) was measured on plug end trims using a helium-driven pycnometer, AccuPyc (Micromeritics, 2014b). Gross volume (*V)* was measured using a displacement technique with graphitized glass spheres (GeoPyc 1360; Micromeritics, 2014a). By combining volume and weight (*w*), effective porosity (ϕ) is calculated with 0.03% accuracy and 0.02% reproducibility.

More details of the analyses, methods, and results are reported by Mielke et al. (2015).

3.3 Rock Typing Using Descriptors

Four descriptors were used for petrotyping in these samples, consolidation (CO), pore type (PORT), groundmass content (GMC), and occurrence of the minerals filling the pores (PFO). Small portions of end trims, core plugs, or drill cores, were systematically broken using a needle probe, metal tweezers, pliers, or a hammer, to record the degree of consolidation as a measure of how hard was to break the sample. The dry and freshly broken rock chips were observed with a binocular microscope using reflected light, or a hand lens, at 20X magnification to identify the percentage of groundmass content in comparison with the particles observed; also to determine the interconnectivity of the visible pore system, and finally to find any indications of cementing minerals or minerals clogging pores. Comparison charts were used as visual aids to estimate percentages of groundmass content. Each descriptor was assigned one class from Table 3.

In combination, the descriptors classes give rocks a number to be identified for, this is a rock type. This numbering scheme follows Sneider's (2010) example for sandstones and carbonates and it is shown in Figure 4.

The descriptors classes are then used in a classification flow diagram that combines rock types into petrotypes (Figure 5).

Table 3: Descriptors classes used for rock typing. After Prieto & Archer (2016).

Descriptor	Class	Features
Degree of consolidation (CO)	1.	Unconsolidated
	2.	Slightly consolidated
	3.	Moderately consolidated
	4.	Moderately well consolidated
	5.	Well consolidated
	6.	Very well consolidated
Porosity type (PORT)	1.	Touching vugs
	2.	Separated vugs
	3.	Interparticle
Groundmass content [%] (GMC)	1	<30
	2.	30-60
	3.	>60
Pore-filling material occurrence (PFO)	1.	Matrix
	2.	Cement

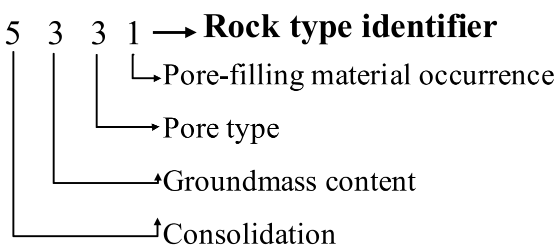

Figure 4: Numbering scheme identifying a rock types, After Sneider (2010).

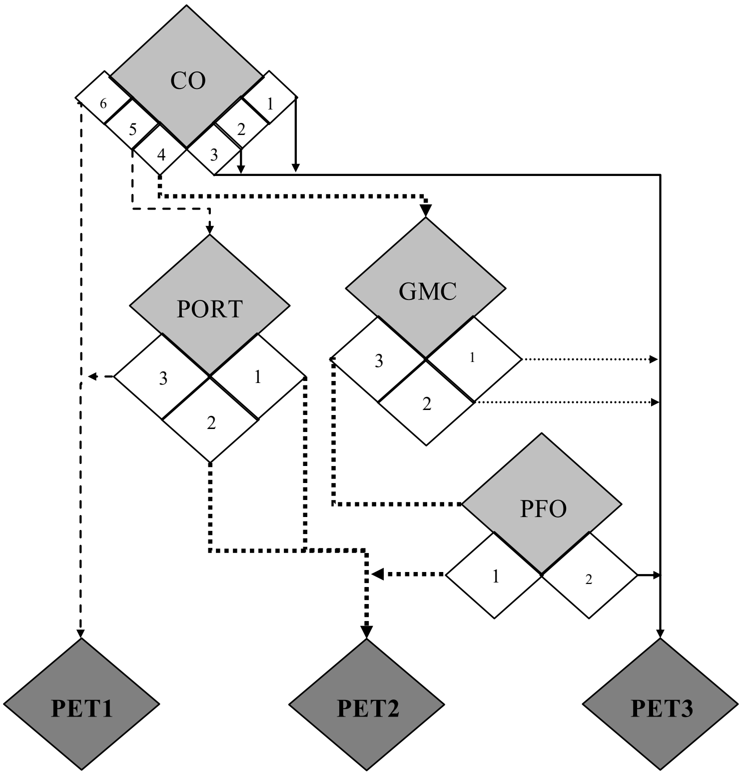

Figure 5: Classification flow diagram of petrotypes using descriptors after Prieto (2018).

3. RESULTS

A sample wellbore displaying the collected and derived data is shown in Figure 6.

Spot observations of four descriptors were carried out. The identified classes are displayed in tracks 5 to 8 in Figure 6, consolidation, pore type, groundmass content, and pore-filling material occurrence, respectively. Descriptors classes were combined into the resulting rock types of tracks 9 and 10. Petrotypes PETs were then generated (track 11) using the classification flow diagram from Figure 5. Each PET is defined mathematically by a set of equations that provide lower and upper limits of values of porosity and permeability (Prieto, 2018).

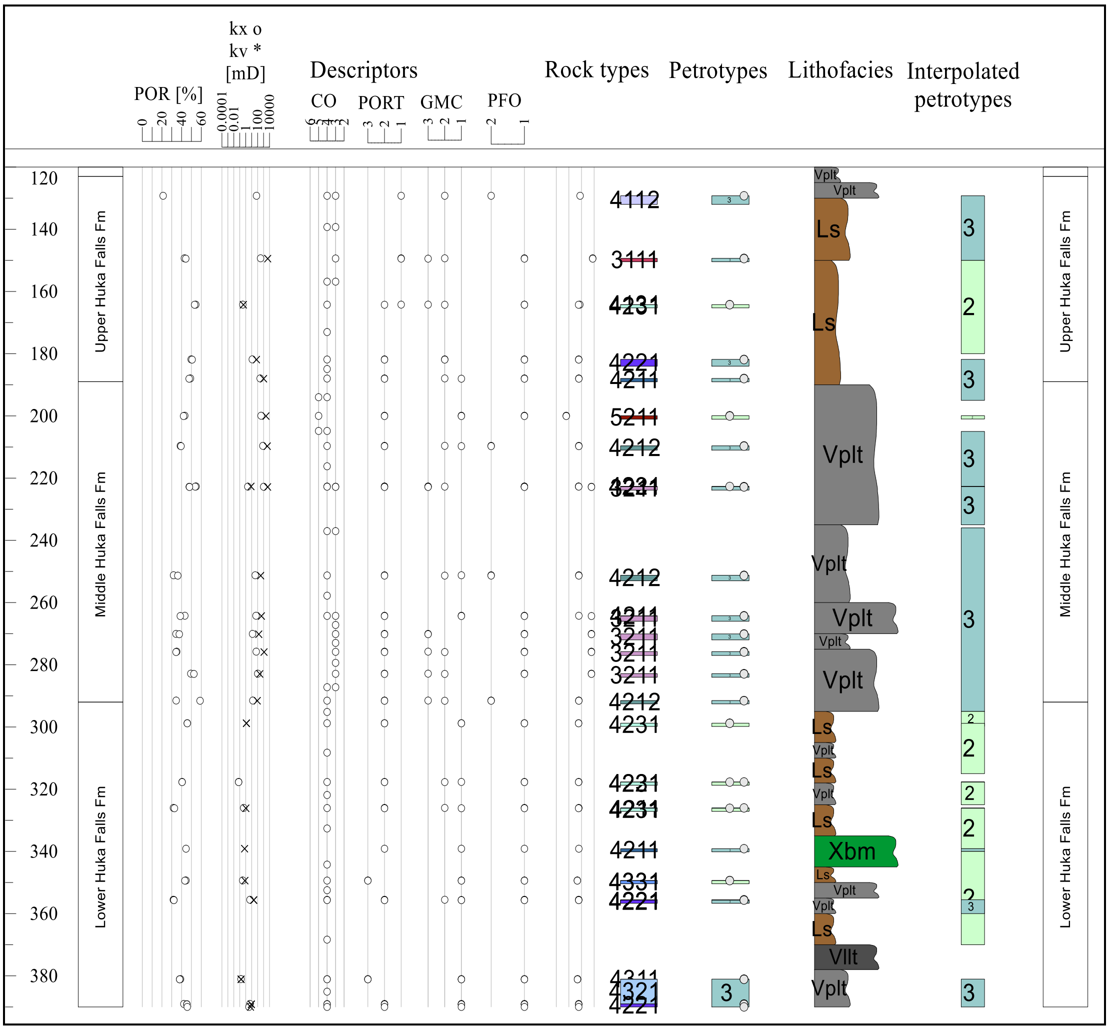

Figure 6: Well THM18 section of the Huka Falls Formation in the TGF. Tracks: 1-depth (meters below ground level), 2-stratigraphic units (Rosenberg, Ramirez, Kilgour, et al., 2009), 3-effective porosity (Mielke et al., 2015), 4-vertical and horizontal air permeability (Mielke et al., 2015), 5-consolidation (CO), 6-pore type (PORT), 7-groundmass content (GMC), 8-occurrence of pore filling material (PFO), 9 and 10- rock type identifier, 11-petrotypes (PET), 12-lithofacies (Cattell, 2015) with VPLT=volcaniclastic pumice lapilli-tuff, Vllt=volcaniclastic lithic and pumice lapilli-tuff, Xbm = lava monomict breccia, Lss = lacustrine sandy and pebbly siltstone, 13-petrotypes , 14- stratigraphic units.

3.1 Interpolating Petrotypes

Lithofacies from Cattel (2016) are available for selected wellbores in TGF (track 12, Figure 6). They were used to exemplify how, by integrating other available information, petrotypes can be interpolated vertically and laterally. Cattel's (2016) graphical well logs are only used as reference and the authors did not use raw data.

It was assumed that, given a spot petrotype observation, the assigned petrotype represented the entire thickness of the corresponding lithofacies unless additional measurements proved it otherwise. Therefore, petrotypes were extended at depth to create more continuous logs (track 13, Figure 6). This exercise was repeated in the available wellbores to translate lithofacies into petrophysical units (Figure 7 and Figure 8).

Additional information can also be used for lateral interpolation of petrophysical units. For example, Cattel (2016) proposed a lithostratigraphic model of the Lower, Middle, and Upper Huka Falls Formations which was used to generate an interpretation of the lateral distribution of petrotypes (Figure 9) along the projected section.

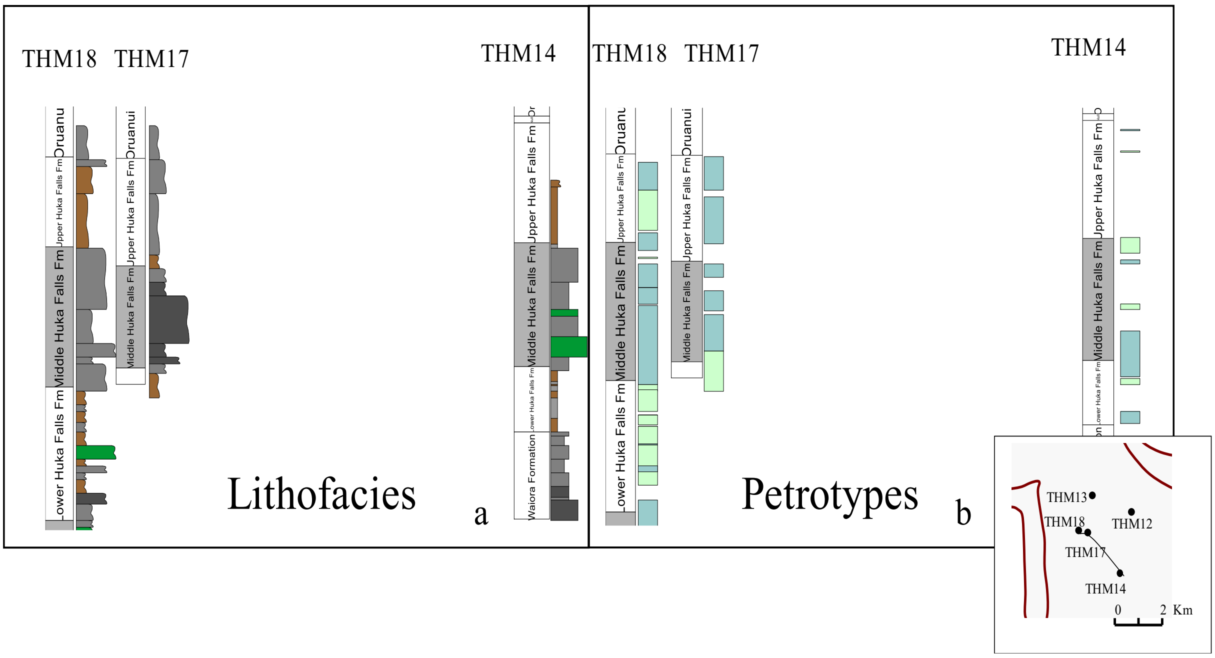

Figure 7: NW-SE cross sections of wells THM18-THM17-THM14 using lithofacies from Cattel (2016) to interpolate petrotypes at depth.

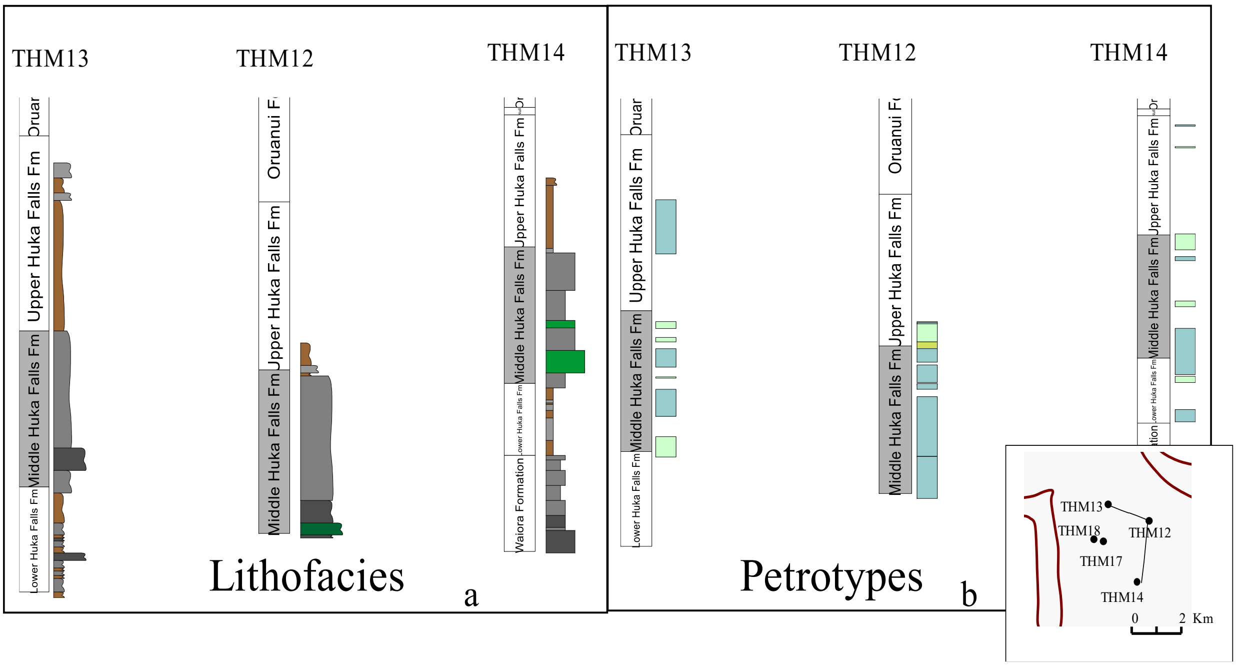

Figure 8: NW-SE cross section of wells THM13-THM12-THM14 using lithofacies from Cattel (2016) to interpolate petrotypes at depth.

Finally, using individual wellbores with more detailed features provided a source for alternative interpretations of the petrotypes spatial distribution. As example, two cross sections were produced to show possible distributions of petrotypes Figure 10.

4. DISCUSSION

Conventional rock classifications include stratigraphic and lithological units. Effective porosity vs. permeability cross-plots of stratigraphic and lithological are shown in Figure 11a and Figure 11b, respectively. It is observed that the LHF formation aligns mostly with PET2. It is a unit comprised mainly of mudstones and siltstones. Both lithologies are mainly characterized by moderate to low consolidation, high groundmass content, absence of interconnected visible porosity, and groundmass in between particles. However, some siltstones are dispersed to PET3. This is a case of a mostly homogeneous stratigraphic unit, and two different lithologies with similar porosity/permeability trends.

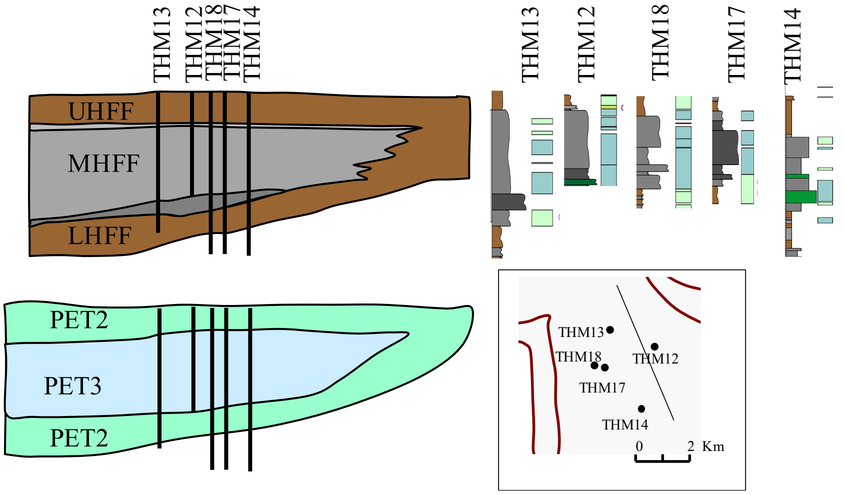

Figure 9. Lithoestratigraphic model of the LHFF, MHFF, and UHFF (after Cattel, 2016). Petrotypes identified in wellbores THM13, THM12, THM18, THM17, and THM14 are used to generate a 2D interpretation of petrotypes.

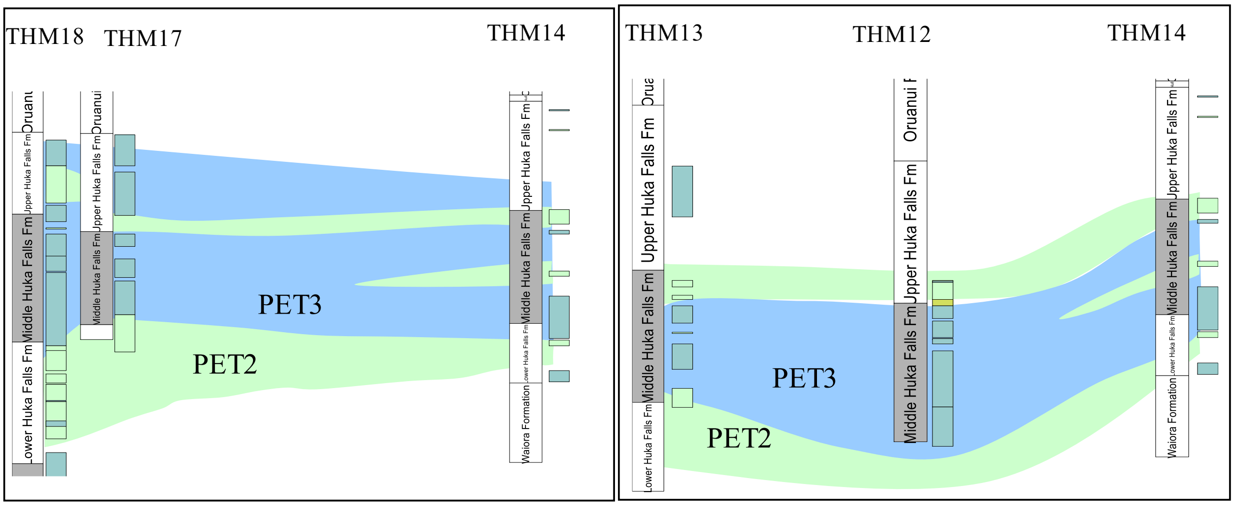

Figure 10: Lateral interpolation of petrotypes in two different cross sections.

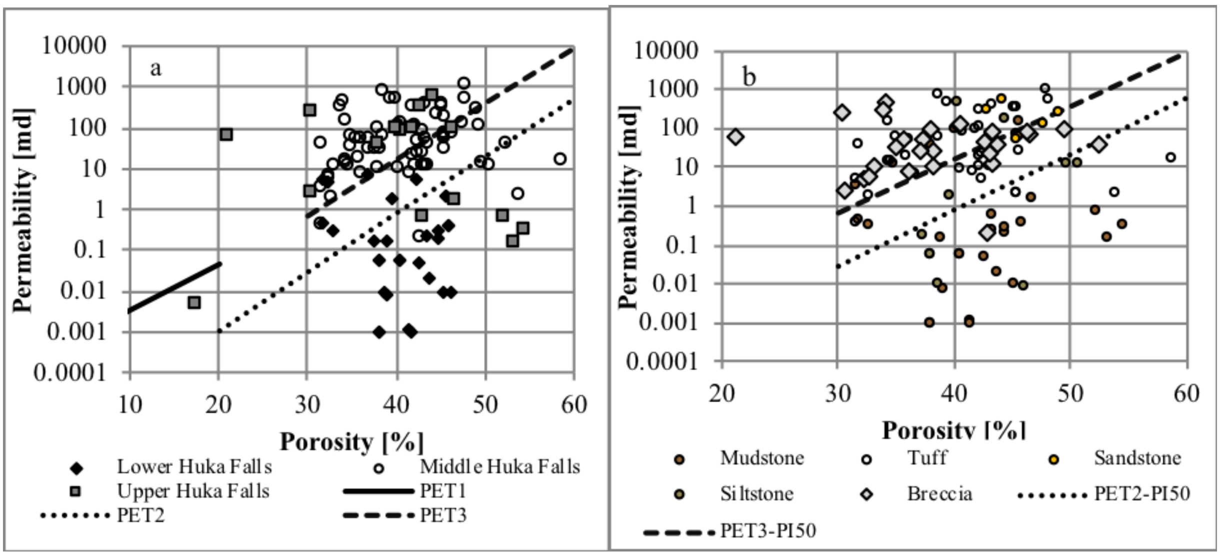

Figure 11: Effective porosity vs. permeability cross-plots showing a) stratigraphic units Lower, Middle and Upper Huka Falls formations, b) lithological units including breccias, tuffs, mudstones, siltstones, sandstones.

In contrast, the MHF formation includes breccias, tuffs, siltstones, and sandstones. Such a heterogeneous stratigraphic unit comprises a wider variety of rocks with different petrophysical trends. Sandstones, breccias, and tuffs group together along PET3 since they are moderately to low consolidated rocks, with medium to low groundmass content. While mudstones and siltstones lie around PET2. In this case as well, petrotypes are closer to the expected porosity and permeability trends than lithologies.

Figure 12a displays rock types in an effective porosity vs. air permeability cross-plot. Rock types are generally distributed in specific areas of the plot allowing rock types with similar porosity/permeability trends to be combined. These bigger groups are the petrotypes shown in Figure 12b. A practical simplification of units by using petrotypes is exemplified, illustrating the advantage of using textural descriptors in complement with stratigraphic and lithological units for reservoir characterization.

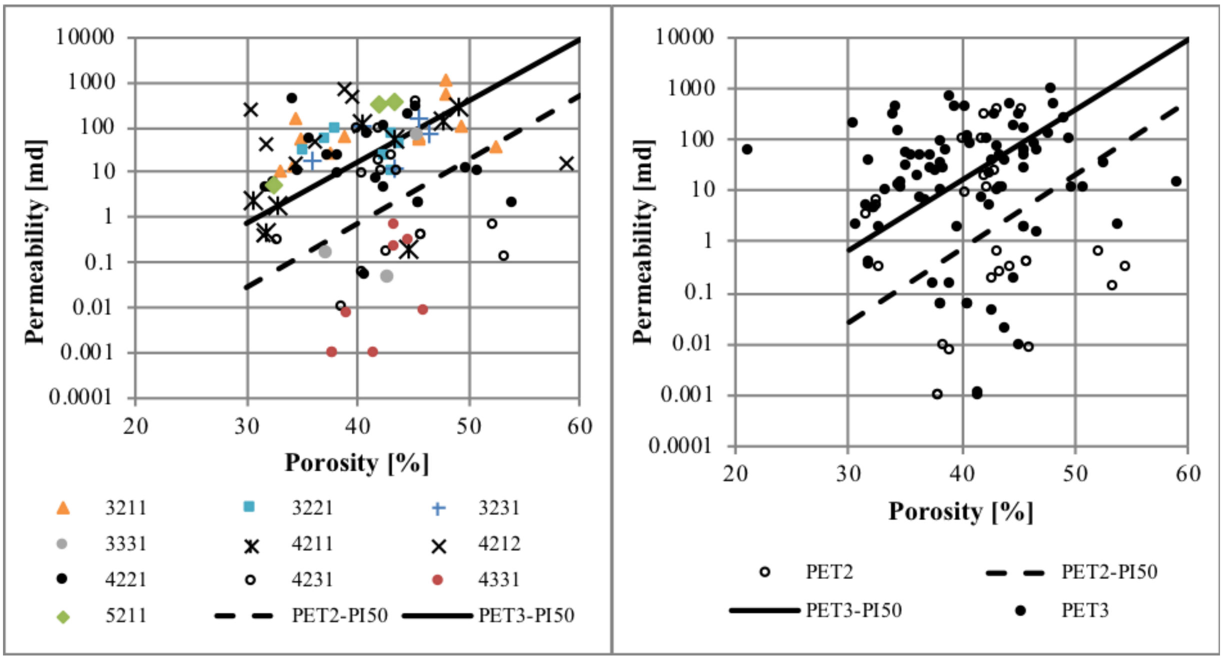

Figure 12: Effective porosity vs. permeability cross-plots of a) rock types and b) petrotypes, recognized in samples of the Huka Falls Formation.

The interpolation presented is used as an example of data integration. However, the information presented in this paper is indicative and could be used as a proposal for further studies. The level of confidence of the interpolations relies on the dataset's accuracy and completeness, and on the modeler's capacity to interpret and correlate petrotypes with other geological features such as lithofacies. The use of analogues and experiences with other reservoirs can be added as well. In this process, a level of confidence needs to be stated by the modeler.

3D modeling is a constructive process that requires progressive steps. Using single wellbore datasets provides means to interpolate petrotypes at depth. Petrophysical cross sections in conjunction with lithofacies models are shown as an example to interpolate petrotypes laterally to build 2D sections. A petrophysical characterization method using petrotypes has the potential to source porosity and permeability at a reservoir scale which makes spot measurements more appropriate for computer simulation.

4. CONCLUSSIONS

A method to classify rocks into petrotypes using descriptors is illustrated. Four textural features, consolidation, pore type, groundmass contents, and pore-filling material, are observed and classed are assigned to each descriptor in each sample. The class numbers are combined to generate rock types which are then used as identifiers for the analyzed rocks. Following a selection scheme, rocks are classified into petrotypes. Petrotypes are groups of rocks with lower and upper boundaries that limit the values of porosity and permeability that can be assigned to a rock. Rocks classified with this method have porosity and permeability values assigned that can be used for numerical modeling.

By integrating additional information in the petrophysical characterization, petrotypes can be interpolated vertically and laterally. Each dataset, their interpretation, and their integration are progressive steps to building 3D models. An illustration of how a lithofacies model provides constraints to interpolate petrotypes in 1D and 2D is presented. This process depends on the quality of the input data and the modeler's interpretation capacity.

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