PETROPHYSICS IN THE CHARACTERISATION OF GEOTHERMAL RESERVOIRS

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ABSTRACT

Geothermal reservoirs models evolve along the reservoir life. They are enriched by the collected data and the knowledge of the geothermal system gained over time. The petrophysical values, such as porosity and permeability, used as inputs for modelling may change too. However, estimating the best values as early as possible contributes to the robustness of the models and improves the outcomes for the field management strategy.

This paper presents a petrophysical characterisation technique based on rocks' textural features or descriptors to provide estimates of petrophysical values. Four descriptors, consolidation, groundmass content, pore type, and pore-filling occurrence, are used as proxies of porosity and permeability. By combining these descriptors, rocks are classified into one of three rock types that have specific trends of porosity and permeability. Two examples of how these rock types are applied in the Tauhara Geothermal Field are presented.

This approach encourages the collection of petrophysical data from the observation of rocks, provides estimated values of porosity and permeability when petrophysical tests are not available, and improves the communication of numerical inputs between geoscientists and engineers.

1. INTRODUCTION

Geothermal energy in New Zealand holds the second place in the sources of electricity generation with 17% of the net national production, 1,709 GWh in March 2018 (MBIE, 2018). To look after this energy source, sustainable reservoir management is required.

Reservoir models are built to provide a representation of what is known of a geothermal system at a given time. Models are tools to make decisions about the best options to utilise the energy contained in the geothermal fields. Optimal reservoir management taps the heat and fluids in ways that avoid the depletion of these renewable resources.

Reservoir models are living subjects. They transform with time, growing in size and detail as more information becomes available or as computation tools evolve to admit more data. Models are improved, and the calibration process is shortened, when better initial estimates and constraints are provided in the conceptual model (Pruess, 1990).

1.1 Petrophysical characterization

The inclusion of petrophysical data contributes to improving reservoir modelling. Complex petroleum volcanic reservoirs have been built with the achievement of history matching and reduced simulation and calibration time (e.g., Ernando & Fathoni, 2012; Li, Zhao, & Han, 2014).

As rocks are subject to formational, diagenetic and tectonic processes, their components, texture, structures, and hence the geometry of the pore system, are shaped. This pore system determines several physical properties that control the fluids and heat flow in the rocks, porosity and permeability among them. Properties in rocks exposed to diagenesis differ from those expected in unaltered rocks. However, it is thought that rocks with similar formational conditions and diagenetic processes commonly share petrophysical features (Archie, 1950). In geothermal settings, diagenetic processes cause that even adjacent rocks display different properties.

Understanding the spatial distribution of these properties, and representing them in integration with other geological information, is the primary objective of reservoir characterization for reservoir modelling. Nevertheless, integrating numerical values of petrophysical properties into reservoir models remains a challenge given the lack of petrophysical data available and the difficulty in capturing the geological complexities at an appropriate scale for modelling.

1.2 Textural descriptors

An approach to include the changing features caused by diagenesis and overcoming the lack of data is provided by using textural features or descriptors.

A study of descriptors observed on hand samples of volcanic and volcanogenic rocks has been carried out (Prieto, 2018). This study used twelve descriptors. Nine of them (surface appearance, rock fabric, particle size, sorting, groundmass content, degree of consolidation, and volume, type, and size of visible porosity) are used in the characterisation of sandstones and carbonate rocks (Sneider, 2010), while three of them (nature, source, and occurrence of the pore-filling material) were included as being of interest for reservoirs in high-temperature settings.

All these descriptors apply to volcanic and volcaniclastic rocks. All descriptors point at the contemporary quality of the rocks despite the processes that have transformed them. It was found that some features display a stronger correlation with porosity and permeability than others, or are better proxies. However, it was observed that there is not a single descriptor that dominates the porosity/permeability relation, but rather a combination of them that have more influence.

1.3 Rock typing

An optimal rock classification for reservoir modelling separates mappable rocks by similar petrophysical properties.

As done in carbonates and clastic reservoirs descriptors can be combined to define petrophysical rock types. (Archie, 1952; Hietala, Conolly, Sneider, et al., 1984; Lucia, 1995). In a section at depth or a field where there are no petrophysical data available, textural descriptors can be used as an additional source of petrophysical information. Such rock typing systems aim at simplifying textural variability in the complex geothermal systems to be used at the reservoir modelling scale.

This paper presents a summary of the results from the investigation on rock typing for petrophysical characterisation by Prieto, Archer, & Sneider (2018) and how these petrophysical types are applied in two selected sections of the TGF (Prieto, 2018).

2. GEOLOGICAL SETTING

The Tauhara Geothermal Field (TGF) is located in the eastern part of the Wairakei-Tauhara Geothermal System, one of the multiple geothermal systems in the Taupo Volcanic Zone (TVZ) (Figure 1) in the North Island of New Zealand. The TVZ is found in the rift structure within the active volcanic arc formed by the convergence between the Australian and Pacific Plates (Wilson, Houghton, Mcwilliams, et al., 1995). TGF is a high temperature (260-300ºC), two-phase fluid geothermal field.

The studied samples cover shallow sections (<850 m) that include the Huka Falls Formation (HFF), Waiora Formation (WAF), the Spa Andesite (SPA) and Racetrack Rhyolite (RR) formations (Figure 1). These include lithic- and vitric-breccias, lithic and vitric lapilli-tuffs, sandstones, mudstones, lavas and autoclastic breccias subjected to different degrees of hydrothermal alteration (weak to high). The dominant composition observed is acidic to intermediate. The stratigraphic descriptions are found in detail in Bignall, Milicich, Ramirez, et al. (2010) and Cattell, Cole, & Oze (2016).

The middle section of HFF, WAF, and RR have identified feed zones that correlate with horizontal boundaries between volcanic strata or with welding zonation in ignimbrite units (Rosenberg, Wallin, Bannister, et al., 2010). The lower HFF section forms an aquitard that controls the fluid flow between the shallow cooler aquifer and the deep hotter reservoirs.

The continuous drill cores and measured petrophysical properties available from TGF provided an exceptional opportunity to study the applicability of textural descriptors in a geothermal system with rock units of different characteristics.

2. METHODS

2.1. Samples

The 190 samples collected in TGF include core plugs of 40 mm in diameter and 20 to 30 mm in length, plug end trims of 10 to 15 mm in length, rock chips from dry and freshly broken samples, and photomicrographs. Selected dried samples were saturated with a blue coloured resin in a vacuum chamber with a maximum vacuum pressure of 40 mbar to highlight features like pore space for image analysis.

2.2. Petrophysical analysis

Core plugs were washed with water, oven dried for 48 hours at 40ºC, and cooled down to room temperature to measure air permeability using steady-state air flow in a columnar permeameter, with a 1 MPa confined Hassler-cell at five pressure stages from 1080 kPa to 5000 kPa. Bulk density was measured on not impregnated

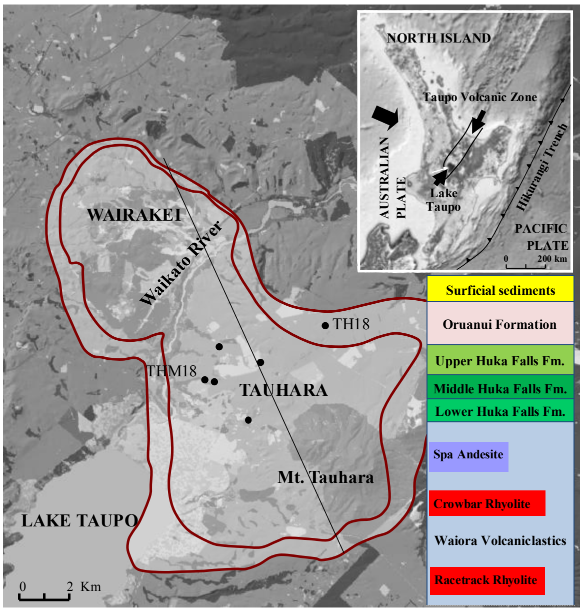

Figure 1. Location map of the Wairakei-Tauhara Geothermal System, limited by its resistivity boundary (dark red line) at 500 mbgl (Rosenberg et al., 2010). Black dots mark the locations of the boreholes where samples were collected for this study. The top inset shows the geographical situation of the TVZ in the North Island of New Zealand, and the right inset shows the stratigraphic column of the shallow section (after Cattell, 2015).

Plug end trims were used to measure bulk density (ρ_g) in a helium-driven pycnometer, AccuPyc (Micromeritics, 2014b) and gross volume (*V*) using a displacement technique with quasi-fluid, fine-grained powder made of graphitised glass spheres (GeoPyc 1360; Micromeritics, 2014a). By combining volume and weight (*w*), effective porosity (ϕ) is calculated using Equation 1 (0.03% accuracy and 0.02% reproducibility).

$$\emptyset = 1 - \left(\frac{w/V}{\rho_g}\right) * 100 = 1 - \left(\frac{w/V}{\rho_g}\right) * 100 \qquad \text{Eq. 1}$$

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

2.3. Textural descriptors

Four descriptors were observed on hand samples of volcanic and volcanogenic rocks:

Groundmass content (GMC) refers to the volume in percentage of solid elements smaller than 0.062 mm filling the pore space between or within particles. GMC excludes those particles selectively replaced by clay minerals.

Consolidation degree (CO) refers to the rock's resistance to disaggregation measured by the way the rock breaks apart (R. M. Sneider, King, Hawkes, et al., 1983).

Pore type (PORT) refers to the dominant pore apace and its interconnectivity (Lucia, 1995).

Pore-filling occurrence (PFO) refers to the manifestation of the material found filling pores, either groundmass or cement.

Drill cores, core plugs, and end trims were fragmented systematically using a needle probe, metal tweezers, pliers, or a hammer to record CO. The dried, freshly broken chips were examined under a binocular microscope with reflected light at 20x magnification to determine GMC, PORT, and PFO. Comparison charts were used as aids to visually identify classes percentage of groundmass content, and visible pore volume (e.g., Folk, 1951). Observation of plugs and end trims were used to compare these results. The microscopic observations were combined with petrographic descriptions (Rosenberg, Ramirez, Kilgour, et al., 2009) to classify PFO.

Additionally, image analyses on digital photomicrographs of pre- and post-impregnated end trims were performed using JMicroVision (Roduit, 2014). The use of a defined colour intensity threshold provided an automatic estimation of the percentage of groundmass content.

The four descriptors are classified with a number assigned to each class following Table 1. Details of the definitions, observation methods, and trends can be found in Prieto (2018).

Table 1. Classification of textural descriptors used in volcanic and volcaniclastic rocks (after Prieto & Archer, 2016).

Descriptor	Class
Groundmass content [%] (GMC)	1. <30 2. 30-60 3. >60
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
Pore-filling material occurrence (PFO)	1. Matrix 2. Cement

2. PETROPHYSICAL CHARACTERISATION

2.1. Descriptors and petrotypes

The four descriptors used for this rock typing scheme (consolidation, pore type, groundmass content, and pore-filling material occurrence) are easily observed on hand specimens or under the microscope. These descriptors are found to show a correlation with effective porosity and permeability (Figure 2).

By using these descriptors in combination (Figure 3) a classification scheme is proposed that divides the rocks according to their petrophysical trends (Figure 4). These clusters apply to the studied volcanic and volcaniclastic samples and are referred to as petrotypes.

Each petrotype can be described mathematically by a best fit-line (Eq 1) and their prediction intervals that can be considered as the low (Eq. 2) and high estimates (Eq. 3) of porosity vs. permeability (Prieto et al., 2018). An example of PET1 is shown in Figure 4. Standardized major axis

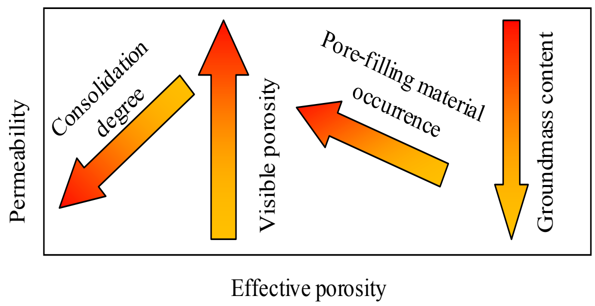

Figure 2. Porosity and permeability trends observed with changing consolidation degree, pore type, pore-filling material occurrence and groundmass content (after Prieto et al., 2018).

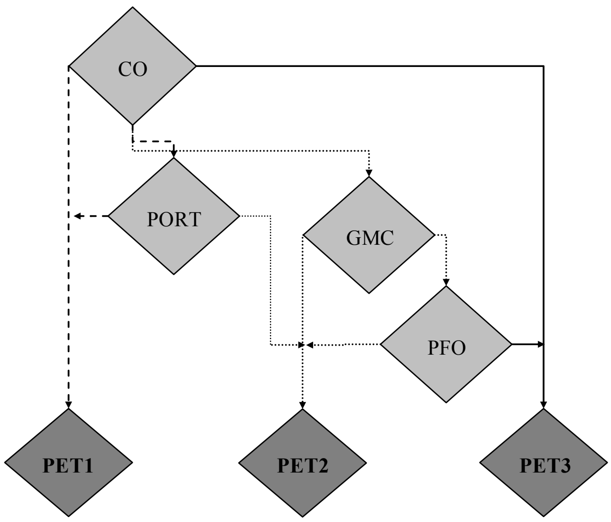

Figure 3. A classification scheme of rock types using textural descriptors (after Prieto et al. 2018).

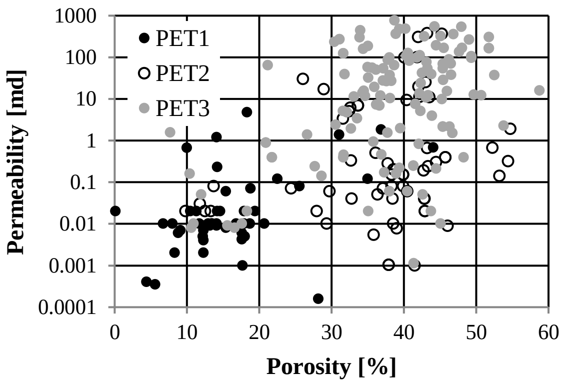

Figure 4. Air permeability vs effective porosity cross-plot of studied samples divided into petrotypes.

regression was used to produce the fit assuming that both variables are independent, with independent measurement error, and that their correlation does not imply causality.

P50 $k = 2.55^{-4} * 10^{11.47\phi}$ **Eq. 1**

P90 $k = 9.75^{-6} * 10^{12.545\emptyset} * 10^{2.455\emptyset^2}$ **Eq. 2**

P10 $k = 0.0054 * 10^{10.947\emptyset} * 10^{2.575\emptyset^2}$ **Eq. 3**

where k is in md and ϕ is in fraction.

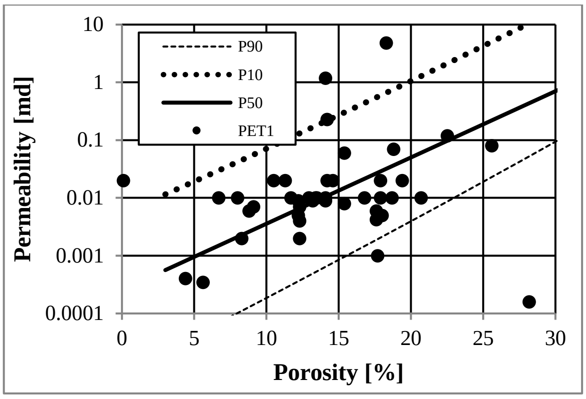

Figure 5. Petrotype PET1 showing the mean trend and the 10 and 90% prediction intervals (after Prieto et al., 2018).

These equations are theoretical representations of the studied rocks and can be used to provide estimates of permeability and porosity ranges. However, they have limitations and can be adjusted as more data is integrated.

3. APPLICATIONS OF PETROPHYSICAL CLASSIFICATION

The observation of samples from the TGF resulted in the identification of textural descriptors and petrotypes at different depths. When combined with petrologic information, the spot measurements were interpolated vertically to provide a continuous interpretation of the petrophysical characteristics at depth. Two sections in two wellbores are shown as examples below (Figure 6 and Figure 7).

3.1. Spa Andesite

This andesite is formed by coherent lavas at the base (approx. 110m) and breccias on top (approx. 90 m) (Figure 6).

The coherent lava (Xi lithofacies) is a very well to well consolidated rock (CO5-6), with micro- or isolated macroporosity (PORT 2-3), low to moderate groundmass content (<60%) (GMC1-2), and matrix or cement filling pores (PFO1-2). It is classified as a PET1 unit.

In the breccias lithofacies (Xbm), one sample available is well consolidated (CO5) with isolated macroporosity (PORT2), moderately groundmass content (GMC2) and cement filling pores (PFO2). Other 10 m of breccia section is embedded in the coherent lava facies and is classified as PET3.

3.2. Racetrack Rhyolite

This rhyolite unit is formed by 65 m of coherent lavas enveloped by 125 m of breccias at top and bottom (Figure 7).

The coherent lava unit (Xl) includes moderately to well consolidated rocks (CO3-5) with interconnected and separated vuggy porosity (PORT1-2), and cement filling pore space (PFO2). Groundmass content varies from <30% to >60% (GMC1-3). This section is mostly classified as PET3. Higher consolidation degree (CO5) is observed only locally, near the middle of the section, and corresponds to a drop of 5% in porosity and one degree of magnitude in average permeability in comparison with its surroundings. This segment is classified as PET2 and may reflect the position of the lava nucleus.

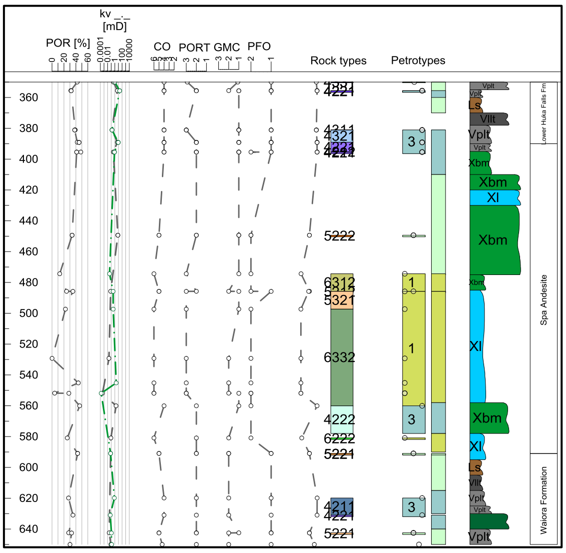

Figure 6. Well section of the Spa Andesite formations in the TGF. Identified lithofacies include coherent lavas, XI, and breccias, Xbm (after Cattell et al., 2016). Tracks show: 1- depth below ground level, 2- measured effective porosity, 3– measured effective horizontal and vertical permeability 4 to 7- consolidation (CO), pore type (PORT), groundmass content (GMC), pore-filling material occurrence (PFO), 8 and 9- rock types identified at each depth, 10- petrotypes at each depth, 11- interpreted interpolation of petrotypes, 12- lithofacies with X-axis varying with estimates mean grain-size (after Cattell et al. 2016), 13- stratigraphic unit.

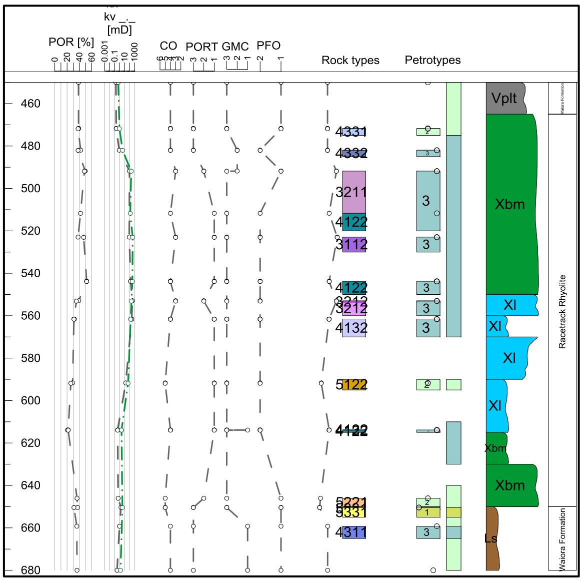

Figure 7. Well section of the Racetrack Rhyolite formation in the TGF. See tracks from Figure 6.

The lower and upper volcanic breccias (Xbm) have a wide variation in descriptors (CO3-4, PORT1-3, GMC1-3, and PFO1-2). These sections are classified as PET3. Two sections (10-20 m thick) of PET 2 and PET1 at the top and bottom are in contact with the under- and overlying rocks of the Waiora Formation.

4. DISCUSSION

In the Spa Andesite, PET2 is used to define the upper brecciated section corresponding to larger grain-sized rocks (track 12 in Figure 6) while PET 3 defines the smaller grain sized breccias intercalated with the coherent lavas and at the top of the unit. In this case, two petrotypes identified for the same Xbm lithofacies provide an indication of the possible variations to be found and that need to be considered among the breccias.

These examples show how the available data can be integrated and interpreted to produce continuous logs at depth. In the Racetrack Rhyolite, the lava nucleus identified as PET2 is thought to potentially reach a thickness of up to 40 m by following the distribution of lithofacies XI. Other case is the thin PET2 section near the rhyolite's lower contact that may reflect the mineral replacement identified by Cattell et al. (2016). These interpretations are subject to reassessment as more information becomes available.

Petrotypes capture the differences between units that have been identified by other conventional classifications such as lithotypes (e.g., coherent lavas as PET1 and breccias as PET2). However, they also highlight the similar physical behavior of rocks that despite having different lithology and varying descriptors may still be represented by the same petrotype. The use of petrotypes is significant as it provides a method to group rocks in a simplified form for their use at reservoir scale.

5. CONCLUSION

An analysis of textural features in volcanic and volcanogenic rocks provided four descriptors that, in combination, are used to propose a classification scheme.

Rocks under this classification are called petrotypes. This classification considers the contemporary quality of the rocks, which marks differences with other conventional rock classifications.

A mathematical representation of the petrotypes is provided by best-fitted equations and the prediction intervals that can be considered as low and high estimates of porosity and permeability. These equations are useful to provide ranges of estimated values, especially when no other petrophysical data are available.

When the petrotypes are combined with other geological information, a continuous interpretation of petrophysical characteristics can be achieved. Two sections displaying the Spa Andesite and the Racetrack Rhyolite formations from the Tauhara Geothermal Field are presented as examples.

The use of petrotypes provided an indication of the rocks' variability that may need to be considered when modelling certain sections at depth, but also proved to be a grouping tool that simplifies petrophysical features. This is significant for the use of petrophysical data at the reservoir models scale.

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REFERENCES

Archie, G. E. (1950). Introduction to petrophysics of reservoir rocks. *AAPG Bulletin*, *34*(5), 943–961.

Archie, G. E. (1952). Classification of carbonate reservoir rocks and petrophysical considerations. *AAPG Bulletin*, *36*(2), 278–298.

Bignall, G., Milicich, S., Ramirez, E., Rosenberg, M., Kilgour, G., & Rae, A. (2010). Geology of the Wairakei-Tauhara Geothermal System, New Zealand. In *World Geothermal Congress 2010* (p. 8). Bali, Indonesia.

Cattell, H. J. (2015). *Volcanic evolution of the Huka Group at Wairakei-Tauhara Geothermal Field, Taupo Volcanic Zone, New Zealand*. University of Canterbury, New Zealand.

Cattell, H. J., Cole, J. W., & Oze, C. (2016). Volcanic and sedimentary facies of the Huka Group Arc-Basin Sequence, Wairakei–Tauhara geothermal field, New Zealand. *New Zealand Journal of Geology and Geophysics*, *59*(2), 236–256. https://doi.org/10.1080/00288306.2015.1102748

Ernando, Z., & Fathoni, A. (2012). Volcanic reservoir characterization of Jatibarang Formation based on an integrated study of petrography, core, FMI and well log. Retrieved May 29, 2014, from http://zulfikariseorengineer.blogspot.co.nz/2011/04/volcanic-reservoir-characterization-of.html

Folk, R. L. (1951). A comparison chart for visual percentage estimation. *Journal of Sedimentary Petrology*, *21*(1), 32–33.

Hietala, R. W., Conolly, E. T., Sneider, R. M., & King, H. R. (1984). Integrated rock-log calibration in the Elmworth Field-Alberta - Part III. In J. A. Masters (Ed.), *Elmworth - Case Study of a Deep Basin Gas Field* (Memoir 38, pp. 243–282). Tulsa, USA: American Association of Petroleum Geologists.

Li, L., Zhao, H., & Han, X. (2014). Rock physical experimental research in Tanan volcanic rock reservoir. *Journal of Applied Mathematics and Physics*, *02*(06), 284–295. https://doi.org/10.4236/jamp.2014.26034

Lucia, F. J. (1995). Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization. *AAPG Bulletin*, *79*(9), 1275–1300. https://doi.org/10.1306/7834D4A4-1721-11D7-8645000102C1865D

Micromeritics. (2014a). GeoPyc 1360. Micromeritics. Retrieved from http://www.micromeritics.com/Repository/Files/GeoPyc_1360_reg_and_TAP.pdf

Micromeritics. (2014b). The AccuPyc II 1340. Retrieved from http://www.micromeritics.com/Product-Showcase/AccuPyc-II-1340.aspx

Mielke, P., Prieto, A. M., Bignall, G., & Sass, I. (2015). Effect of hydrothermal alteration on rock properties in the Tauhara Geothermal Field, New Zealand. In *World Geothermal Congress* (p. 10). Melbourne, Australia.

Ministry of Business Innovation & Employment (MBIE). (2018). *Quarterly electricity generation and consumption data updates*. Wellington, New Zealand: Ministry of Business, Innovation and Employment.

Prieto, A. M. (2018). *Systematic characterisation of geothermal reservoirs* (submitted Doctoral dissertation). The University of Auckland.

Prieto, A. M., & Archer, R. (2016). Rock typing in geothermal reservoirs: application of textural descriptors. In *European Geothermal Congress* (p. 8). Strasbourg, France.

Prieto, A. M., Archer, R., Lawrence, M. J. F., Mclay, J., Sneider, J. S., & Golla, G. (2018). *Rock typing for the characterisation of geothermal reservoirs*. Manuscript in preparation.

Pruess, K. (1990). Modeling of geothermal reservoirs: fundamental processes, computer simulation and field applications. *Geothermics*, *19*(1), 3–15.

Roduit, N. (2014). JMicroVision: image analysis toolbox for measuring and quantifying components of high-definition images. Retrieved from http://www.jmicrovision.com

Rosenberg, M. D., Ramirez, L. E., Kilgour, G. N., Milicich, S. D., & Manville, V. R. (2009). *Tauhara subsidence investigation project : geological summary of Tauhara wells THM12-18 and THM21-22 and Wairakei wells WKM14-15 2009/309*. Retrieved from https://contact.co.nz/Assets/pdfs/corporate/environmental/P3GeoscienceReport.pdf

Rosenberg, M. D., Wallin, E., Bannister, S., Bourguignon, S., Sherburn, S., Jolly, G., … Links, F. (2010). *Tauhara Stage II Geothermal Project: Geoscience report. GNS Science consultancy reports 2010/138*. Wairakei, New Zealand. Retrieved from https://www.contactenergy.co.nz/web/pdf/environmental/P5SubsidenceReport.pdf

Sneider, J. S. (2010). 7. Rock Types. In *Integration of rocks, log and test data*. Tulsa, USA: Petroskills.

Sneider, R. M., King, H. R., Hawkes, H. E., & Davis, T. B. (1983). Methods for detection and characterization of reservoir rock, Deep Basin gas area, Western Canada. *Journal of Petroleum Technology*, (September), 1725–1734.

Wilson, C. J. N., Houghton, B. F., Mcwilliams, M. O., Lanphere, M. A., Weaver, S. D., & Briggs, R. M. (1995). Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: A review. *Journal of Volcanology and Geothermal Research*, *68*(95), 1–28.