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Rock Typing in Geothermal Reservoirs, a Textural Approach

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ABSTRACT

Reservoir rocks are found in a broad spectrum of effusive and volcaniclastic rocks in the geothermal fields around the world. The varying textures of these rocks are the result of the combination of formational and diagenetic processes that may strongly modify the primary rock properties. The observed textures are often related to the petrophysical properties.

The petrophysical properties impact reservoir performance affecting fluid storage and flow capacity. Yet analytical petrophysical data is not fully integrated into geological and numerical models due to the complexity of the rocks, the sparsity of measurements, and the lack of understanding of the available data.

This paper describes key textural parameters recognizable in hand specimens, including particle size, consolidation and porosity type, as a base for a rock-typing system applicable to geothermal reservoirs. Some or all of these textural parameters are proxies for porosity and permeability trends. A catalog, currently being developed, representing different petrophysical rock types will allow the comparison of cuttings of rocks with unknown petrophysical properties to samples with known properties. The purpose of the catalog is to provide reliable estimates of petrophysical properties where no analytical data, cores or electric logs are available.

1. INTRODUCTION

The governing equations of geothermal numerical models require the input of petrophysical properties that determine the rock quality as reservoir, i.e., porosity (ϕ) and permeability (k), to simulate the fluid flow through the geothermal system (Pruess, Olderburg, and Moridis, 1999). Studies characterizing volcanic reservoirs in oil, gas and geothermal fields (e.g., Ernando and Fathoni, 2012; Hadi, Harrison, Keller, and Rejeki, 2005; Steckhan and Sauer, 2010; Yuan, Qiquan, Xu, Hu, and Wang, 2006; Zhao et al., 2008), showed that methods of interpreting and using petrophysical data require non-conventional integration of studies, including rock descriptions, laboratory measurements, geophysical surveys and electric logs interpretation, to determine the best petrophysical properties at reservoir scale to better understand the reservoir hydraulic behavior and improve the numerical models accuracy.

Despite their importance to the models, measured petrophysical properties are not systematically integrated in the characterization of geothermal reservoirs (Farooqui et al., 2009), including those in New Zealand, due to the limited availability of suitable petrophysical data. The lack of data is worsened by the variable hydraulic behavior of effusive and volcaniclastic rocks found, a scarcity of electric well logs and seismic surveys (Wallis, McCormick, Sewell, and Boseley, 2009), and a shortage of studies integrated into reservoir models.

The reservoir-rock quality of sandstones and carbonates can be estimated from the relationship existing between permeability and pore geometry, where the latter is usually determined by textural rock parameters such as particle size and sorting. The analyses and combination of these textural parameters have resulted in empirical correlations and petrophysical classifications that have been used as prediction tools in similar and uncored reservoirs (Archie, 1952; Lucia, 1995; Sneider and King, 1984).

Textures observed in volcanic rocks such as grain size, fabrics and vesicularity, result from characteristics of the source material, e.g., magma composition, viscosity; and formational processes, e.g., magma transport, cooling, welding (Sruoga and Rubinstein, 2007). Present-day textures, as in carbonate rocks, often differ from the primary textures due to digenesis (dissolution, cementation, thermal alteration). This difficulty to predict digenesis makes it challenging to predict petrophysical properties for a numerical model based on stratigraphic position, formation age, chemical composition and other conventional rock classifications.

This paper describes the use of surface appearance, rock fabric, particle size, sorting, argillaceous content, consolidation and visible porosity as textural parameters recognizable in hand specimens that aid in the prediction of reservoir-quality rocks. These textural parameters are compared to the measured porosity and permeability of a set of volcaniclastic rocks of the Tauhara Geothermal Field, New Zealand. We are opening a discussion about their applicability to predict reservoir quality of rocks in geothermal fields.

2. REGIONAL CONTEXT

The study samples are from shallow monitoring boreholes (Rosenberg, Ramirez, Kilgour, Milicich, and Manville, 2009) of the Tauhara Geothermal Field, the eastern part of the Wairakei-Tauhara Geothermal System located in the central Taupo Volcanic Zone (TVZ) (Figure 1), a rift structure on the North Island of New Zealand within the active volcanic arc formed in the convergent margin between the Pacific and Australian plates (Wilson et al., 1995).

Studied samples belong to the Huka Falls Formation (HFF), a sequence of clastic and volcaniclastic rocks accumulated in an extensive lake on top of the Waiora Formation and prior to the Oruanui eruption of Taupo Volcano (26,500 years ago). HFF is recognized as the cap rock of the Wairakei-Tauhara Geothermal System (Rosenberg, Bignall, and Rae, 2009). It is subdivided in three units, the Upper, Middle and Lower HFF members The Upper and Lower HFF are fine-grained volcaniclastic sediments, and Middle HFF, a shallow aquifer, consists of coarse-grained volcanic and volcaniclastic rocks.

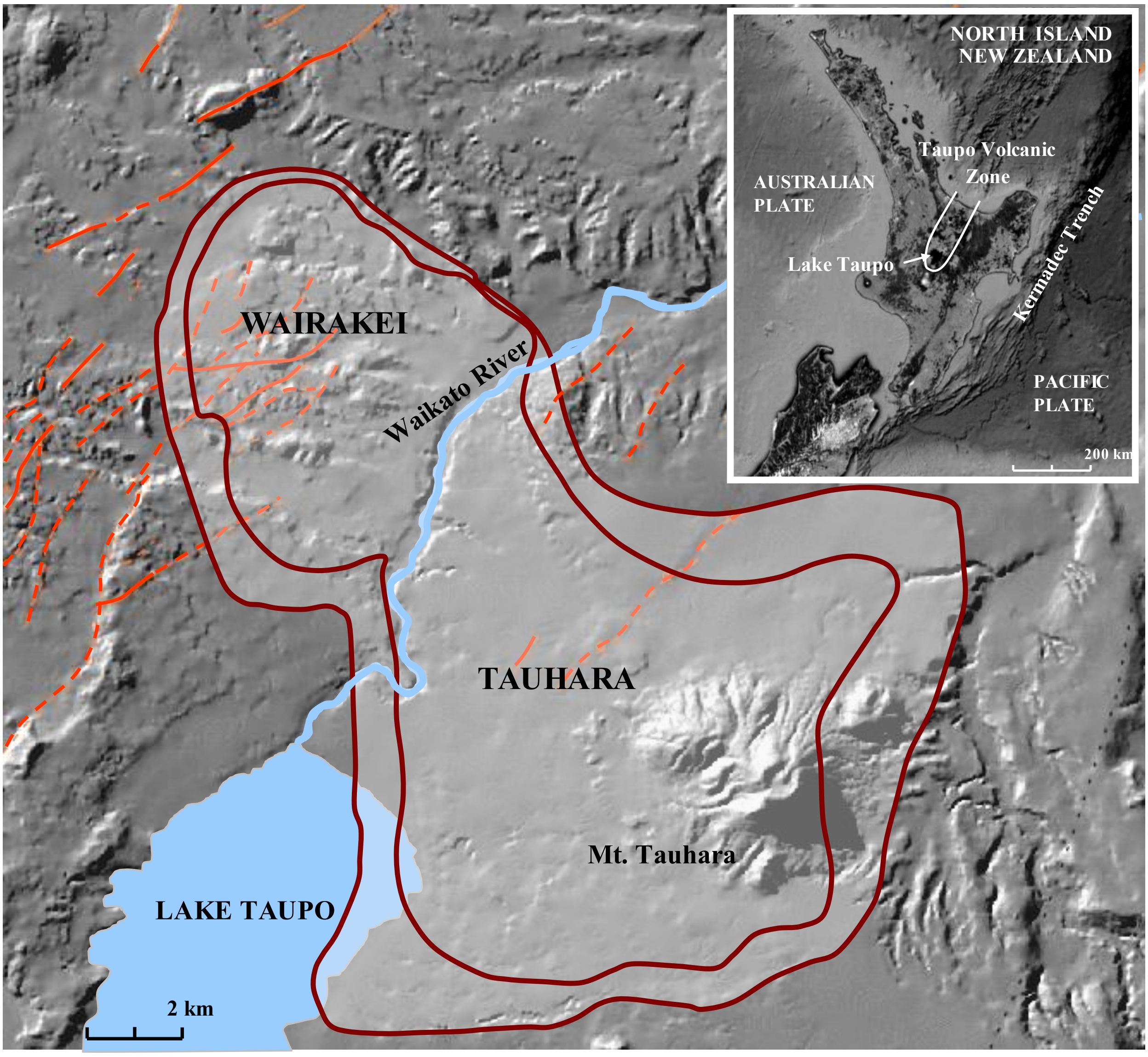

Figure 1: Location map of the Wairakei-Tauhara Geothermal System (light gray shaded area), limited by its resistivity boundary at 500 mbgl (dark red lines) (after Rosenberg et al, 2010), and fault traces (orange lines) (http://data.gns.cri.nz/geology/). Inset shows geological setting of the Taupo Volcanic Zone.

Lithologies logged on site from drill-cores (Rosenberg, Ramirez, et al., 2009) include vitric lapilli tuffs and breccias from the Lower HFF; vitric lapilli tuffs, lithic and vitric breccias, and sandstones from Middle HFF, and siltstone, sandstones, and vitric-lithic breccias from the Upper HFF.

3. USING TEXTURAL PARAMETERS IN VOLCANIC ROCKS

Archie (1950) summarized the limitations faced by geologist and engineers to determine the net pay thickness of progressively deeper oil and gas carbonate reservoirs in the 1950's. Archie cited an increasing need to use indirect data sources such as cuttings and electric logs to determine porosity, permeability and thickness because of the rocks heterogeneity, lack of cores and lack of production data. Similar limitations are faced today characterizing geothermal volcanic reservoirs.

In the decades of investigation that followed, the relationships between indirect data sources and reservoir properties were analyzed. A host of characterization workflows and methodologies in sandstone and carbonate reservoirs were generated to improve the estimation of reservoir-rock quality and, hence, the discovery and recovery of hydrocarbon reserves (Al-marzouqi et al., 2010; Aplin, Dawans, and Sapru, 2002; Lucia, 2007; R. M. Sneider, Stolper, and J.S. Sneider, 1991). The new methodologies provided means of predicting reservoir-rock quality where data is scarce and limited (Corelab, 2013).

It was found that the permeability and geometry of the pore network of a rock; size, volume, and interconnectivity of pores; control a rock's hydraulic behavior. Archie (1950); Lucia (1983); Sneider, King, Hawkes, and Davis, (1983), and others, have shown that the pore geometry of sandstones and carbonate rocks is generally determined by particle size, sorting, packing, consolidation and degree of cementation, and that these traits are reflected on the surface appearance of the rock. They have shown that particles size, sorting, and packing, condition the size and shape of the original or primary pores; compaction and cementation reduce their volume; and dissolution increases it. This means, the contemporary pore geometry of a rock may be different from the primary one, and it gives information about the formational and diagenetic processes that have affected it.

Understanding the permeability-pore geometry relationship of geothermal reservoirs of New Zealand could significantly improve the characterization of reservoir properties given the limited existence of drill-cores to provide direct data source and the complexity of the diagenetic processes (including hydrothermal alteration) modifying primary rock textures. There is significant potential to develop and use empirical correlations to predict reservoir behavior considering the large amount of available drill-cuttings. In order to develop these empirical correlations it is necessary to determine which textural parameters are feasible defined, observed, quantified, classified, and to what extent they impact the hydraulic properties of volcanic rocks.

Eight textural parameters that affect the reservoir quality of sandstones and carbonate rocks have been adapted as needed to fit common terminology in volcanic rocks (Prieto, n.d.): surface appearance, rock fabric, particle size, sorting, argillaceous content, consolidation and type and size of visible porosity. **Rock surface appearance** (SA) reflects the distribution and size of the rock particles (Archie, 1952), giving an indication of the pore space between them, i.e., interparticle porosity (Lucia, 1995). **Rock fabric** (RF) refers to the relative difference in size and distribution of the solid elements (e.g., particles, matrix or groundmass, pore-filling materials) that form the structure of the rock including dominant elements and supporting framework (Choquette and Pray, 1970). **Particle size** (PS) of the dominant elements in the rock, i.e., particle or groundmass, is the main control of the interparticle porosity (Lucia, 1983). The degree of uniformity of the particles forming the rock structure is referred as **sorting** (S). **Argillaceous content** (AC) refers to the volume percentage of groundmass and other materials filling the pore space, e.g., clays, glass, other cements. **Consolidation** is a qualitative indicator of cementation and compaction measured by the way the rock breaks apart (Sneider and King, 1984). **Visible porosity** includes the **size** (PORS), **volume** (PORV) and **type** (PORT) of pores visually identifiable in the rocks.

4. METHODOLOGY

4.1 Samples and petrophysical analyses

Forty-five drill-cores from four shallow boreholes collected from the Tauhara Geothermal Field were selected to perform textural descriptions and petrophysical analyses. Petrographical descriptions from Rosenberg, Ramirez et al. (2009) were used as reference.

Oven-dried core plugs of 4 cm in diameter and 2 to 3 cm in thickness with smooth surfaces were used for permeability measurements (Mielke, Prieto, Bignall, and Sass, this issue). Permeability was measured in a Hassler cell columnar permeameter that uses steady-state air flow to calculate effective gas permeability. Approximately 2 cm wide end trims were sawed off of each core and used for density and porosity measurements. Bulk density of each sample was calculated using a gas-driven pycnometer. The results were combined with the volume measured by a displacement technique that utilizes a fine-grained powder made of graphitized glass spheres, a pseudo-fluid, to calculate effective porosity.

End trims were broken apart to describe textural parameters on freshly broken, dry rock surface. Part of them was dyed with blue epoxy and polished to highlight the pore geometry. Digital photomicrographs of the samples before and after impregnation were taken with reflected light to determine textural parameters using image analysis techniques.

4.2 Description of textural parameters

Archie's (1952) classification to describe *rock surface appearance* based on micro (or non-visible) porosity within the groundmass was used. The term "particle" is used here to refer to grains and crystals as in Lucia (1983). We adjusted Lucia's (1995) classification, introduced as a modification of Dunham's (1962) fabric classification of carbonate rocks, to describe the contemporary *rock fabrics* considering particles smaller than 0.0625 mm as groundmass. This concept is in some way equivalent to the textural features of the fabric concept in igneous petrology found in Best (2002). *Particle sizes* were classified according to the Wentworth-Udden-Krumbein particle size scale with very small particles size estimated from microscope observation at 60x magnification. *Consolidation* classes were used as in Sneider and King (1984). Percentage of *argillaceous content*, visible *pore sizes* and *pore volume* were classified as in Sneider (2010), while *pore types* classification was simplified from Lucia's (1995) description.

Freshly broken and dried end trims were examined under a binocular microscope with reflected light at 20x magnification to determine classes of *rock surface appearance*, *rock fabrics*, *particle size, and visible porosity*. Visual comparison charts were used as aids to identify classes for *particle size*, *sorting* (Beard and Weyl, 1973) and percentage of *argillaceous content* and *visible pore volume* (Folk, 1951).

Additionally, image analyses on digital photomicrographs of pre- and post-impregnated end trims were performed using JMicroVision to complement and compare visual classification looking for consistency between estimates. The use of a defined *color intensity threshold* provided estimation of the percentage of *argillaceous content,* and *visual porosity.* Particles forming the rock framework were classified by size using *object extraction* and analyzed to calculate sorting by the Folk and Ward (1957) graphical method in GRADISTAT v 8.0 (Blott, 2010).

Classes of textural parameters applied in this study are shown in Table 1.

5. RESULTS AND DISCUSSION

Our observations show that textural parameters used as a way to estimate reservoir-rock quality in sandstones and carbonates can be adapted and used to describe volcaniclastic rocks. Not all the parameters show a clear correlation with measured porosity and permeability in the selected samples, opening a discussion about their applicability. The results draw our attention to textural features that can be described as part of the geological logging process that may allow a fast, on-site estimation of the rock-reservoir quality of geothermal fields.

5.1 Textural parameters

Eight textural parameters (surface appearance, rock fabric, particle size, sorting, argillaceous content, consolidation and type and size of visible porosity) were used to describe a selected set of volcaniclastic samples. All of them are describable in the context of geothermal reservoirs and potentially can be included as standard practice for on-site geological logging while drilling.

Regarding the parameters definition, equivalent textural terms already in use in the igneous petrology literature are found, e.g., well sorted = equigranular (Table 1). Surface appearance and consolidation degree for example, although not used before in this context, are applicable in the way defined for sandstones and carbonate rocks. Some definitions are reappraised to better fit the observation, e.g., rocks with particles smaller than 0.062 mm and sugary surface appearance are classified as granular as in Sneider (2010), even though according to Archie (1952) they would be classified as *chalky* rocks.

All the parameters are observable on hand samples or under the microscope and acceptable descriptions are achieved with training and consistency within the working team. Particular challenges include differentiation of classes 6, 7 and 8 of particle size, and estimation of volume percentages of argillaceous content and porosity. Observation under the microscope at high magnification (e.g., 60x) aids differentiating particle size. Assessing percentages requires practice from the analyser as using visual estimations and comparison charts can contribute up to 10% to overestimating proportions (Flügel, 2010). Impregnated samples and photomicrographs analysis were used to assist the estimation of volume percentages and identification of pore space as an alternative for this assessment.

Table 1. Classification of textural parameters

TEXTURAL PARAMETER	CLASSIFICATION	
Rock surface appearance	1. Compact - crystalline or resinous look 2. Chalky - dully and unreflective appearance 3. Granular (also sucrose) – sugary look	
Rock fabric	1. Particle-dominated/particle supported with open interparticle space 2. Particle-dominated/particle-supported with open interparticle space partially filled 3. Groundmass-dominated/particle-supported with interparticle space filled 4. Groundmass-dominated/ groundmass-supported with >10% particle content 5. Groundmass-dominated/ groundmass-supported with <10% particle content	
Particle size	1. >2 mm 2. 1 - 2 mm 3. 0.5 - 1 mm 4. 0.25 – 0.5 mm	5. 0.12 – 0.25 mm 6. 0.06 – 0.12 mm 7. 0.02 – 0.06 mm 8. <0.02 mm
Sorting	1. Equigranular 2. Moderately equigranular 3. Inequigranular 4. Very inequigranular 5. Bimodal	
Argillaceous content	1. 0 – 15% 2. >15 – 25% 3. >25 – 35% 4. >35 – 45%	5. >45 – 55% 6. >55 - 65% 7. >65 – 75%
Consolidation	1. Unconsolidated 2. Slightly consolidated 3. Moderately consolidated	4. Moderately-well consolidated 5. Well consolidated 6. Very well consolidated.
Visible porosity		
Pore volume	1. >35% 2. >30-35% 3. >25-30% 4. >20-25%	5. >15-20% 6. >10-15% 7. >5-10% 8. <5%
Pore size	POR-A non-visible. Estimated from surface appearance PORS-B. <0.125 mm PORS-C 0.125-2 mm PORS-D>3 mm	
Pore types	1. Interparticle 2. Intraparticle 3. Separated vugs 4. Touching vugs 5. Fractures	

Concerning quantifiable parameters, i.e., percentage of particles, argillaceous content and porosity, we find that analyzing different types of samples contributes with generating better estimates, e.g., percentages of AC from visual estimation on an end trim and from image analysis on a impregnated sample are consistent. This is the main principle of developing a catalogue that allows comparison between different types of samples with known petrophysical parameters.

In terms of establishing classes, some original classes were simplified, e.g., very well sorted and well sorted into equigranular; while others were described in more detail at this stage of the assessment, e.g., argillaceous content in 10% intervals. The parameters classification is an ongoing process and will be addressed in future work.

Combining different rock samples and descriptive methods increases the reliability of using textural parameters to analyze reservoir-rock potential and aids the analyzer while achieving a level of training to perform the descriptions with samples on-site while drilling. The definition and classification of the parameters is subject of current work to extend their use to other volcanic rocks, e.g., lavas.

5.2 Correlation of textural parameters with measured porosity and permeability

Our results show that surface appearance, groundmass particle size, argillaceous content and consolidation appear to correlate with the measured effective porosity and air permeability. Individual cross-plots are shown to present trends within parameters classes and we open the discussion regarding their applicability in estimating reservoir-rock potential in volcaniclastic rocks.

Cross-plots of porosity vs. permeability show existing trends for rocks with similar hydraulic characteristics (Figure 2). It is assumed that a rock with higher permeability and certain porosity has better flowing properties than one with lower permeability and same porosity, and will be referred as having better reservoir quality. The scattering of these plots is due to the high variability of the rock samples included.

Figure 2A shows surface appearance classes. A sample with *compact* appearance has the lowest permeability of the set, and rocks with *chalky* appearance show lower k/ϕ ratio than *granular* ones. This, as initially defined by Archie (1950), is related to the particles structure, ranging from tightly interlocked with no porosity between them that define the compact look, through less interlocked and small particles with chalky appearance, to bigger particles interlocking at different angles with space between them causing the granular appearance.

Rock fabric is represented by classes 2 and 4 (Figure 2B). There is no clear effect of particles- or groundmass- dominated fabrics on the distribution of porosity-permeability contrary to what is observed in carbonate rocks. Questions have arisen around the effects of different proportion of filled interparticle space between classes 1 and 2 and particle content between classes 4 and 5. Variations to this classification will be explored in future work to confirm the observed trend. Nevertheless, rock fabric affects the relevance of other parameters, e.g., argillaceous content in groundmass-dominated rocks in contrast with particle-dominated rocks, so it is a parameter that needs to be described.

A stronger influence of particle size was expected as a controller of k/ϕ. Sneider and King (1984) differentiated PS for sandstones into 6 classes by combining 0.5 - 2 mm (classes 2 and 3) and <0.0625 mm (classes 7 and 8) particle sizes into two classes. In addition Lucia (1983) highlighted important boundaries for carbonate rocks at 0.1 and 0.02 mm. While difficult to observe, we identified classes 6 and 7, but no samples were classified as class 8. We recognise there is a limitation in describing PS < 0.06 mm so complementing ways of determining small classes are being explored. Predominant PS observed in particle- and groundmass-dominated rocks are shown in Figure 2C and 2D respectively. In the first case, no trend is observed for the small number of samples represented. In the latter case, rocks with predominant particles >0.06 mm in the groundmass tend to have slightly better quality compared to rocks with smaller PS class 7. This suggests a boundary at 0.06 mm that can be used as lower PS boundary in a similar way as in sandstone reservoirs.

All the rocks are composed of sand- to gravel-size particles in very fine sand- to clay-size groundmass, therefore, their sorting is classified as very inequigranular or bimodal, as generally is in volcaniclastic rocks. With the aim of analysing sorting of the particle fraction, Figure 2E displays classes within the particle-dominated samples (RF class 2) but no relationship is observed. Although we recognise the number of analyzed samples is small, sorting using the established classification does not seem to affect hydraulic properties.

Figure 2F shows classes of percentage of argillaceous content. Rocks with argillaceous content higher than 45% tend to have lower k/ϕ ratio. There is not clear distinction between classes 3 and 4; and neither there is between classes 5, 6 and 7; suggesting similar intervals as in Sneider (2010) for descriptions at 20x, i.e., 1) difficult to see, 2) <50%, 3) 50-75%, 4) 75-80%, 5) >80%. The nature of the argillaceous content including composition (e.g., clays, silica, volcanic glass) and origin (e.g., alteration, dissolution and precipitation) is not addressed by us at this stage.

Consolidation classes are presented in Figure 2G. The class 6 sample is a compact rock, highly consolidated with small pore space. It is observed a tendency of better consolidated rocks (classes 4 and 5) to have higher k/ϕ ratio than the less consolidated ones (classes 2 and 3). The results are contrary to what was expected, this is, less consolidated rocks with larger porosity and better flowing properties. In this case, less consolidated rocks also correspond to groundmass-dominated rocks with higher argillaceous content (Figure 2F) and groundmass with smaller particle sizes (Figure 2E), which can be related to the presence of alteration clay species identified in petrographic descriptions (Rosenberg et al., 2009). This agrees with the general trend in altered siliciclastic rocks where drilled sections with higher clay content are related with stability issues and wash-outs and at the same time with poor quality reservoir-rocks. Consolidation, as interpreted here in the sense of Sneider and King (1984), refers to both mechanical and chemical compaction. An inverse correlation between effective porosity and depth has been observed in samples from Wairakei Geothermal Field (Mielke, 2009). Yet, the correlation between the nature of the material filling the pore space (cements vs. clays) and chemical compaction has not been addressed, which suggests the importance of differentiating the nature of argillaceous content for future work.

The size and type of pores are of great importance to the pore geometry and, therefore, to the hydraulic capacity of the rock. The volume of visible porosity of the studied samples, including PORS-B and -C, is shown in Figure 2H in intervals of 5%. Interparticle porosity (PORT class 1) in pores <0.125 mm (PORS-B) was identified in all the samples, but the degree of interconnectivity is hardly observable with the used techniques. Only few samples display other porosity type as shown in Figure 2I. Pore types class 2 and 3 are isolated types. There is not clear relationship between visible porosity and k/ϕ ratio, which may be due to poor interconnectivity of observed pores and suggests a stronger control of micro-porosity on the hydraulic rock properties.

The control of micro-porosity is partially confirmed by the correlation of argillaceous content and interparticle porosity calculated as in Lucia (1983)

$$\phi'_p = \frac{\phi_T - \phi_v}{1 - \phi_v} \tag{1}$$

where ϕ'_p, ϕ_T, ϕ_v are the interparticle porosity of the groundmass, total porosity (measured), and separated vuggy porosity (PORT 1, 2, 3 and PORS-B, C and D), respectively. Figure 3 shows that the percentage of argillaceous content in the rocks is proportional to the difference between the measured and visible porosity, this is micro-porosity contained in the groundmass.

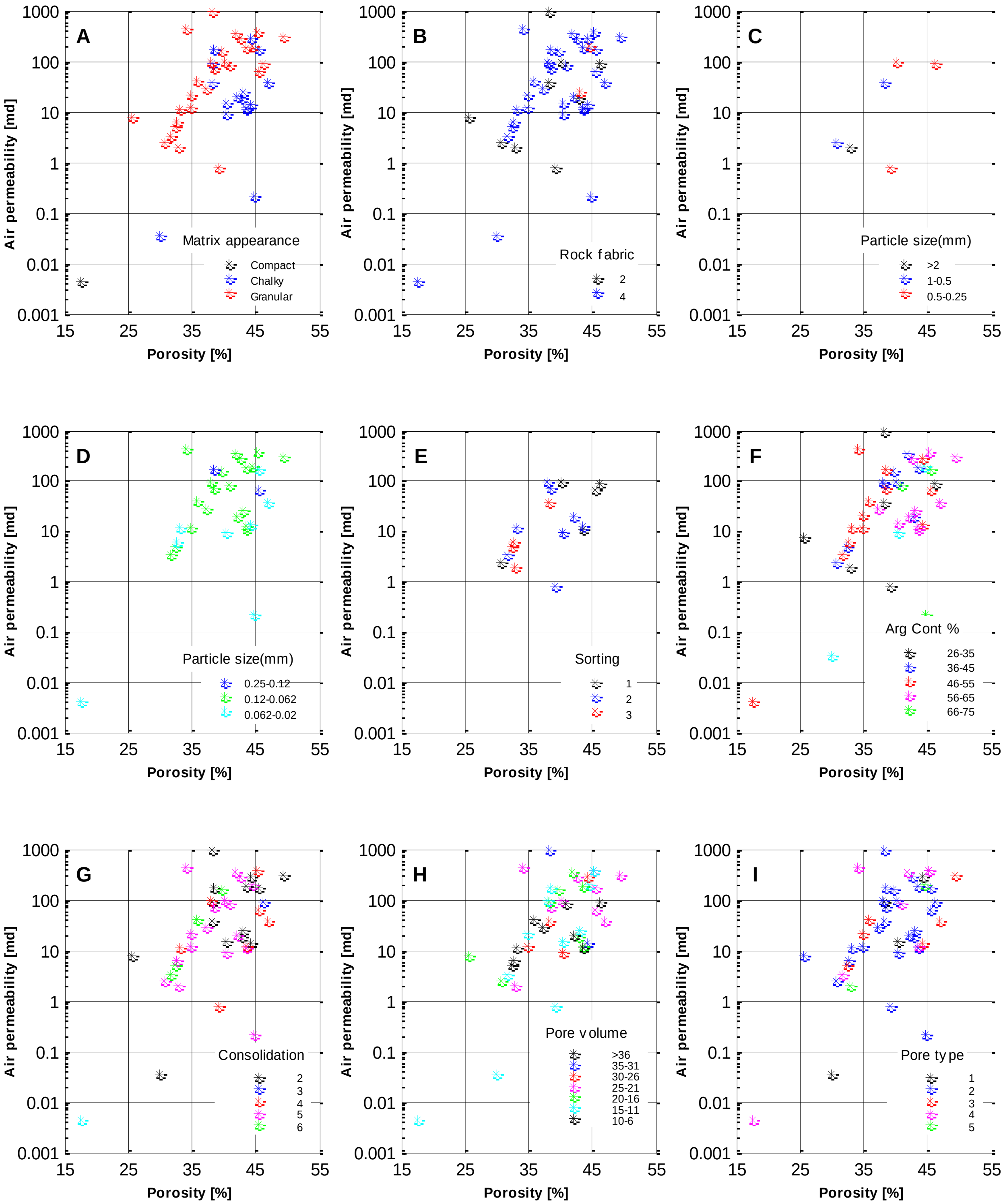

Figure 2: Cross plots of effective porosity vs. air permeability comparing textural classes (A) surface appearance; (B) rock fabric; (C) particle size in samples with groundmass-dominated fabric; (D) particle size in samples with particle-dominated fabric; (E) sorting within samples with particle dominated fabric; (F) argillaceous content in groundmass-dominated samples; (G) consolidation; (H) percentage of visible porosity; (I) porosity type.

Textural parameters showing a relationship with measured effective porosity and air permeability confirm their control on the pore geometry of the rock. Rock fabric is used to assess the dominant elements of the rock and determine the use of other parameters during the descriptions, e.g., argillaceous content which is to be described in groundmass-dominated rocks. The use of sorting in particle-dominated rocks is questioned but the number of analyzed samples is small to make conclusions. Consolidation will be addressed in terms of compaction and cementation in future work. Although at this stage it is concluded that the micro-porosity has a stronger effect on the hydraulic properties of volcaniclastic rock than visible pores, the total porosity (micro and visible) plays an important role in other aspects of the petrophysical characterization, e.g., evaluation and integration of electric logs, and is important for future work. The effects of these parameters are still to be analyzed in other types of volcanic rocks.

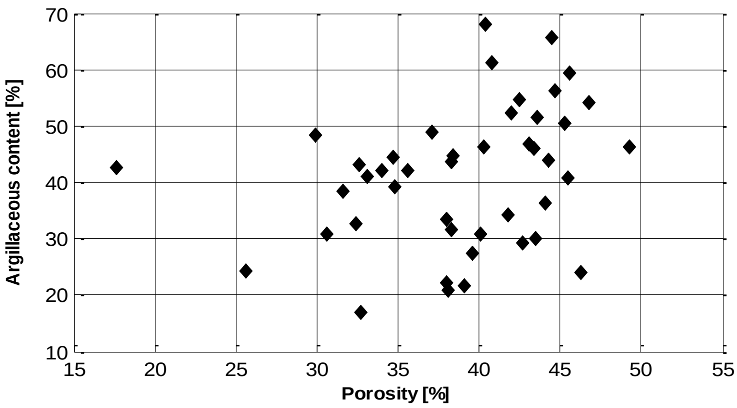

Figure 3: Cross plot of interparticle porosity and argillaceous content

6. CONCLUSION

Textural parameters are used in sandstones and carbonate reservoirs to provide estimates of the rock quality as they reflect features of the contemporary pore geometry and, hence, permeability. Rock classification systems based on these parameters allow predicting petrophysical properties when no cores are available. These parameters have been used: surface appearance, rock fabric, particle size, sorting, argillaceous content, consolidation, and type and size of visible porosity in volcaniclastic rocks, and we have observed a relationship with measured effective porosity and air permeability.

The selected parameters are defined by adapting terms already used in igneous petrology literature, and are described on hand samples and under the microscope by using visual estimations and comparison charts. Practice and consistency within the working team is required to provide reliable descriptions, with the potential of being a fast assessment of reservoir-rock quality on-site while drilling. Different types of samples are to be used when available to ensure results consistency. A catalogue will be developed to provide a set of samples with known petrophysical properties that allow comparison of drill-cuttings with unknown properties.

Surface appearance, groundmass particle size, argillaceous content and consolidation show control on the measured porosity and permeability of the studied samples. Rocks with granular appearance, particle size >0.06 mm in the groundmass, and argillaceous content <45% show a better reservoir-rock quality compared to other samples. Consolidation shows a particular trend that needs to be addressed in future work to understand the effects of compaction and cementation separately. Rock fabric, sorting and visible porosity show no individual control on k/ϕ ratio. Nevertheless, rock fabric determines the relevance of other parameters by defining the dominant elements of the rock; and visible porosity can be used in the integration of electric logs for reservoir characterization in future work; therefore, they are to be described.

The classification within textural parameters and their combination in a rock-typing system are currently subject of study in order to expand their use to other volcanic rocks found in geothermal fields as a tool to estimate petrophysical properties where samples and data are restricted.

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REFERENCES

Al-marzouqi, M. I., Bush, I., Griffiths, R., Gzara, K. B. M., Roth, J., Montaron, B., and Poirier-coutansais, X.: Resolving carbonate complexity, In *Oilfield Review Summer 2010,* Schlumberger, (2010), 40–50.

Aplin, G. F., Dawans, J.-M. L., and Sapru, A. K.: “New insights from old data”: identification of rock types and permeability prediction within a heterogeneous carbonate reservoir using diplog and openhole log data, *Proceedings,* 10th International Petroleum Exhibition and Conference, Society of Petroleum Engineers, Abu Dhabi (2002).

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

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

Beard, D. C., and Weyl, P. K.: Influence of texture on porosity and permeability of unconsolidated sand, *AAPG Bulletin*, *57*(2), (1973), 349–369.

Choquette, P., and Pray, L. C.: Geological nomenclature and classification of porosity in sedimentary carbonates. *The American Association of Petroleum Geologists Bulletin*, *2*(2), (1970), 207–250.

Corelab: *Joint Industry Projects - Rock Catalogs/Databases.* Retrieved August 09, 2013, from http://www.corelab.com/irs/jip-rock-catalogs-databases.

Dunham, R. J.: Classification of carbonate rocks according to depositional texture. In W. E. Ham (Ed.), *Classification of carbonate rocks-a symposium*, *AAPG Memoir 1* (pp. 108–121). Houston: American Association of Petroleum Geologists. (1962).

Ernando, Z., and Fathoni, A.: Volcanic reservoir characterization of Jatibarang Formation based on an integrated study of petrography, core, FMI and well log. *Indonesian Petroleum Association*. http://zulfikariseorengineer.blogspot.co.nz/2011/04/volcanic-reservoir-characterization-of.html. (2012).

Farooqui, M. . Y., Hou, H., Li, G., Machin, N., Neville, T., Pal, A., … Yang, X.: Evaluating volcanic reservoirs. *Oil Field Review*, *3*(3), (2009), 36–47.

Flügel, E.: *Microfacies of carbonate rocks: analysis, interpretation and application (*2nd ed.). Berlin Heidelberg: Springer-Verlag. (2010).

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

Hadi, J., Harrison, C., Keller, J., and Rejeki, S.: Overview of Darajat reservoir characterization : a volcanic hosted reservoir, *Proceedings,* World Geothermal Congress 2005, Antalya, Turkey, 24–29. (2005).

Lucia, F. J.: Petrophysical parameters estimated from visual descriptions of carbonate rocks : a field classification of carbonate pore space, *Journal of Petroleum Technology*, *35*(March), (1983), 629–637.

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

Lucia, F. J.: *Carbonate reservoir characterization - An integrated approach* (2nd ed.). Berlin Heidelberg: Springer-Verlag. (2007).

Mielke, P.: *Properties of the reservoir rocks in the Geothermal Field of Wairakei/New Zealand*. (Diploma thesis). Technische Universität Darmstadt, Germany. (2009).

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

Prieto, A. M.: *Rock typing Oil and Gas applications on geothermal reservoirs os New Zealand* [Science Report]. Manuscript in preparation. (n.d.).

Pruess, K., Olderburg, C., and Moridis, G.: *Tough2 User's guide, version 2.0* (Report LBNL-43134). Berkely, California, USA: Lawrence Berkley National Laboratory. (1999).

Rosenberg, M. D., Bignall, G., and Rae, A. J.: The geological framework of the Wairakei–Tauhara Geothermal System, New Zealand, *Geothermics*, *38*(1), (2009), 72–84. doi:10.1016/j.geothermics.2009.01.001

Rosenberg, M. D., Ramirez, L. E., Kilgour, G. N., Milicich, S. D., and Manville, V. R.: *Tauhara subsidence investigation project: geological summary of Tauhara wells THM12-18 and THM21-22 and Wairakei wells WKM14-15,* (2009/309 [Consultancy Report]. Wairakei: GNS Science. (2009).

Rosenberg, M., Wallin, E., Bannister, S., Bourguignon, S., Sherburn, S., Jolly, G., … Links, F. *Tauhara Stage II Geothermal Project: Geoscience report* (2010/138) [Consultancy report]. Wairakei: GNS Science (2010).

Sneider, J. S.: *Integration of rocks, logs and test data*, Tulsa: Petroskills. (2010).

Sneider, R. M., and King, H. R.: Integrated rock-log calibration in the Elmworth Field-Alberta - Part I. In J. A. Masters (Ed.), *Elmworth - Case Study of a Deep Basin Gas Field (Memoir 38)* (pp. 205–214).Tulsa: American Association of Petroleum Geologists. (1984).

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

Sneider, R. M., Stolper, K., and Sneider, J. S.: Petrophysical properties of seals, *Proceedings*, AAPG Annual Convention, Dallas, TX, USA. (1991).

Sruoga, P., and Rubinstein, N.: Processes controlling porosity and permeability in volcanic reservoirs from the Austral and Neuquén basins, Argentina. *AAPG Bulletin*, *91*(1), (2007), 115–129, doi:10.1306/08290605173.

Steckhan, J., and Sauer, R.: Introduction of a rock typing methodology in crystalline basement reservoirs (Yemen). *Search and Discovery*, *40524,* (2010).

Wallis, I., McCormick, S., Sewell, S., and Boseley, C.: Formation assessment in geothermal using wireline tools – application and early results from the Ngatamariki Geothermal Field, New Zealand, *Proceedings*, *33th* New Zealand Geothermal Workshop, Rotorua, New Zealand. (2009).

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

Yuan, S., Qiquan, R., Xu, Z., Hu, Y., and Wang, Y.:. Reservoir characterization of fractured volcanic gas reservoir in deepzone, in *Proceedings,* SPE Annual Technical Conference and Exhibition, Society of Economic Geologists, Beijing, 1–12. https://www.onepetro.org/conference-paper/SPE-104441-MS. (2006).

Zhao, W., Zou, C., Feng, Z., Hu, S., Zhang, Y., Li, M., … Yang, H.:. Geological features and evaluation techniques of deep-seated volcanics gas reservoirs, Songliao Basin. *Petroleum Exploration and Development*, *35*(2), 129–142, doi:10.1016/S1876-3804(08)60019-1. (2008).