

Permeability and Thermal Conductivity Measurements of Near Surface Units at the Wairakei Geothermal Field, New Zealand

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ABSTRACT

Thirty one outcrop and drill core samples (to about -500 mRL) from geothermal wells from Te Mihi, western Wairakei Geothermal Field (New Zealand), have been analysed for their mineral assemblage and hydrothermal alteration, thermal conductivity, permeability, bulk rock porosity and density, as part of a study on the affect of the geological parameters on the thermal conductivity. At Wairakei, cores of Huka Falls Formation (soft, lacustrine-deposited tuff and sediments), Waiora Formation (variably consolidated, medium hard, hydrothermally altered volcanic tuff) and Karapiti Rhyolite (hard, altered rhyolite lava and breccias) were analysed from wells WK223, WK224 and WK227 (unaltered/least altered field margin); WK206, WK207, WK212, WK219 and WK247 (Te Mihi upflow zone); and WKM14, WK205, WK210, WK213 and WK221 (infield, south and east of Te Mihi). The effect of hydrothermal alteration (rank and intensity) on thermal conductivity was tested by analysing samples from the same stratigraphic units from different wells, albeit with a range of styles of hydrothermal alteration (e.g. clay-dominated argillic, characterised by a progression from smectite to illite-dominated clay assemblages, to propylitic). Results demonstrate a good correlation between porosity and thermal conductivity, but no clear relationship between permeability and thermal conductivity. We also compared permeability and thermal conductivity from the Wairakei Field samples with data from rocks in central Europe.

1. INTRODUCTION

Geothermal energy is an energy source with potential to play a major role in helping meet the Earth's future's energy demand. The Earth's heat can be used in many ways, from small thermal (ground-sourced) heat pumps, that supply single houses with warm water, up to a large and complex district heating systems, or for generating electricity. Most technical systems are based on tapping hot fluids from a geothermal reservoir by means of production (i.e. extraction) wells. Prior to drilling production wells, the reservoir potential, and its resource capacity, should be resolved. Knowledge of the rocks properties in the geothermal area is often poor, and data on the rock (and reservoir) properties are often not available.

To obtain information on the physical (thermal) properties of the potential reservoir rock expensive investigations have to be undertaken. This would typically involve the drilling of core samples, which is costly and time-consuming, and consequently the drilling phase of a project may only cut

cores at intervals of every couple of hundred metres, or possibly not at all. This brings up the question, whether the results obtained from the few recovered cores are representative of the non-analysed part(s) of the formation. Thus, the relationship between geothermal parameters and geological factors have to be determined. Promising starting points to achieve this goal, and the subject of this paper, is to analyse thermal and geological parameters from archived drill cores, along with the compilation of a rock property/geothermal database.

Permeability and thermal conductivity are of utmost interest to estimate the (heat) efficiency of a geothermal reservoir. However, correlations between thermal conductivity and permeability are only feasible when both parameters are measured for the same sample, so anisotropic factors like stratification can be taken into account.

In the past, drill cores from multiple locations in Central Europe have been tested for permeability and thermal conductivity (Sass and Buß, 2007; Sass et al., 2008). In a comparative study, we tested cores from the Wairakei Geothermal Field, New Zealand. We tested: 1) whether thermal conductivity correlates with permeability; 2) the relationship of both parameters with respect to stratigraphic affinity and rock texture; 3) the effect of hydrothermal alteration on permeability and thermal conductivity; and 4) the effect of the porosity on the thermal conductivity. As part of the study, we also compared Wairakei data with results from selected rocks units drilled in Central Europe.

2. EXPERIMENTAL SETUP

2.1 Measurement of Permeability using a Gas Pressure Minipermeameter

Conventional methods for determining bulk rock permeability commonly return an integrative result that refers to the whole sample. A gas pressure permeameter permits an infinite number of pointwise measurements, which can be assigned to individual layers of a rock sample.

Permeability measurements were performed at Technische Universität Darmstadt, using a combined columnar and Minipermeameter, with conditioned pressured air as the measuring medium. The Minipermeameter is a pressured-air driven gas-permeameter, which allows precise measurement of the permeability at the surface of a rock sample. The sample's surface can be plane or curved (e.g. a drilling core), but has to be smooth. The measurement is fast and non-destructive. A probe attached to an adjustable pneumatic ram is pressed perpendicularly on the sample's surface with a pre-defined pressure. The probe consists of an injection nozzle and a circular adapter with a seal washer. The exchangeable adapter has an inner diameter of 4 mm and an outer of 25 mm, and is manufactured in

different shapes to accommodate the best fitting on the sample's surface. The seal washer of neoprene or caoutchouc is placed between the stamp and the sample to avoid leakages. Pressured air is injected into the sample through the central opening in adapter and the seal, initiating a particular flow-through. After a brief period a quasi-stationary volumetric flow rate builds up, which can be described by equation 1:

$$Q_i = \frac{p_L}{p_i} M_i \quad (1)$$

where Q_i , p_L , p_i , M_i are volumetric flow rate, atmospheric pressure, injection pressure and mass flow rate.

Thus, permeability can be described by equation 2:

$$K = \frac{Q_i \eta p_i}{r(p_i^2 - p_L^2) F_G} \quad (2)$$

where K , η , r , F_G are permeability, dynamic viscosity, radius of the adapter and geometric factor.

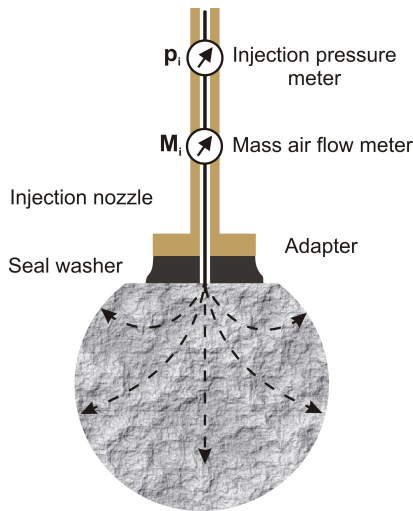


Figure 1: Measuring principle of the Minipermeameter

The geometric factor accommodates flow geometry and allows determination of the volume of space the gas passes through. It is calculated by the calibration routine of the columnar permeameter. The columnar permeameter utilises cut slices of drill core. The columnar permeameter is also used to validate results from the Minipermeameter. Thus, error can be limited to a maximum deviation of 5%. The measurement method does not consider reservoir temperature, pressure and fluid properties. Samples are

therefore measured oven-dry to enable comparability. The measurement of oven-dry samples also significantly improves the measurement accuracy, as moist samples cannot be measured within the desired error limit.

2.2 Measurement of Thermal Conductivity

Thermal conductivity was measured using the Optical Scanning Method (Figure 2) after Popov (1999), as it allows relatively quick measurements of samples with differing quality, and a detailed study of the anisotropy of their thermal conductivity.

A heat source passes along the sample to heat up the sample surface. No contact is made with the samples, with the measurement made by two infrared temperature sensors.

Heat source and temperature sensors move with a constant speed and have a fixed separation distance to each other (Figure 3). The heat source focuses on the sample's surface, whereby the sample is heated up of approx 4 °C. The temperature is measured prior and after heating.

The determination of the thermal conductivity (λ) is based on the comparison of the induced temperature differences between standards (of known thermal conductivity λ_s) and the test sample material of unknown thermal conductivity. The ratio of θ and θ_s is proportional to the measured electrical potentials U and U_s , and is described by (3):

$$\lambda = \lambda_s \left(\frac{\theta_s}{\theta} \right) = \lambda_s \left(\frac{U_R}{U} \right) \quad (3)$$

Samples with prismatic and cylindrical shape are measured. Standards are made of a material with a similar thermal conductivity as the core sample. Measurements are done using oven-dry and moist samples, and have an accuracy of up to 3%. In certain soil-mechanical conditions the measurement can also be done on unconsolidated material.

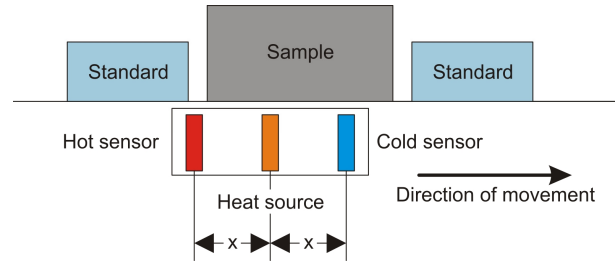


Figure 3: The Thermal Conductivity Scanner

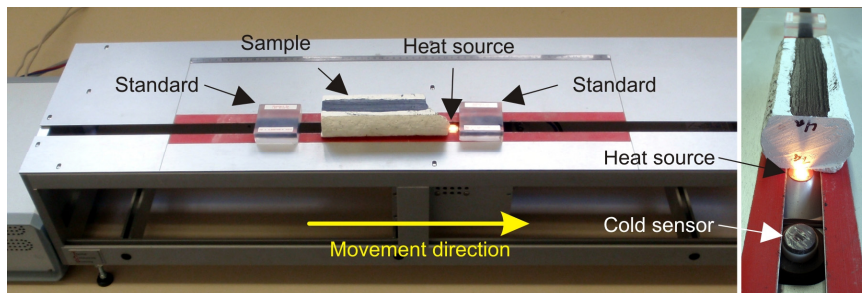


Figure 2: The Optical Thermal Conductivity Scanner

3. WAIRAKEI GEOTHERMAL FIELD

The Wairakei Geothermal Field is part of the Wairakei-Tauhara geothermal system and is located in the southeastern edge of the Taupo Volcanic Zone (TVZ, New Zealand), about 7 km northeast of Taupo Town. The TVZ represents the most active area of Pliocene to Quaternary volcanism and geothermal activity in New Zealand. It extends from Ruapehu volcano in the central North Island to White Island in the Bay of Plenty, and for >3000 km along the Tonga-Kermadec plate margin. The TVZ evolved due to the westward subduction of the Pacific plate beneath the Indian-Australian plate, and has erupted a total volume of about 20 000 km³ volcanic material.

The Wairakei-Tauhara geothermal system is defined by an electrical resistivity boundary (Figure 4). Resistivity measurements since the 1960's have indicated a contiguous low resistivity zone (about 5 Ωm) at 500 to 1000 m depth, caused by geothermal effects, which contrast sharply with the much higher electrical resistivity (> 100 Ωm) of unaltered cold rock outside the field. The geothermal system has a NW-SE extent of ~15 km, with a width of ~5 km at Wairakei and ~10km at Tauhara.

Drilling has been underway at Wairakei for >60 years, with wells completed at various locations. Initially, the Eastern Borefield was the main production area, with wells located in a NW-SE trending valley, commonly known as Steam Valley. After reservoir pressure and temperature declined steam production shifted to the Western and Te Mihi Borefield areas. The Western Borefield has about 30 wells drilled to a depth of ~600 m, and is located to the northwest of the Eastern Borefield, roughly in the centre of the Wairakei Geothermal Field. The Western Borefield produces about 50% of the steam for the Wairakei Power Station. The Te Mihi Borefield is situated in the northern/northwestern part of the Wairakei Geothermal Field. Here, as well as tapping the deep liquid reservoir, dry steam is extracted from a shallow (330 to 500 m) high pressure steam zone hosted in the Karapiti 2A Rhyolite.

3.1 Geological Framework

The Wairakei Geothermal Field is located in a deep, broad structural depression in the greywacke (regional) basement, infilled with layered volcanic and fluvial deposits, and rhyolitic dome intrusion/lavas. The strata and structures represent up to 1 Ma of volcanism, fluvial sedimentation in the area, as well as regional tectonic and volcanic events.

3.1.1 Stratigraphy

The stratigraphy follows the concept of Rosenberg et al. (2009):

The geological basement of the TVZ is formed by Jurassic metasedimentary greywacke of the **Torlesse Terrane**. The greywacke basement has yet not been drilled in the Wairakei area, but recently at Tauhara. Interpretation of regional gravity and seismic data point to the volcanic and volcanoclastic cover above the TVZ basement being at least 2.5 km thick.

Volcanoclastic and sedimentary deposits above the greywacke basement, but underlying Wairakei Ignimbrite, are collectively termed **Tahorakuri Formation**. Little is known about the age and stratigraphic detail of the Tahorakuri Formation, as it has only been penetrated in three Wairakei wells. The formation is at least 650m thick and is in character similar to the volcanic/volcanoclastic

strata of the Waiora Formation (although Tahorakuri Formation has more andesite lava/breccia subunits).

Tahorakuri Formation is covered by ignimbrites of the 340 to 320 ka Whakamaru-Group Ignimbrites, which are widely spread throughout TVZ. At Wairakei, these ignimbrites are called **Wairakei Ignimbrite**. The formation has been penetrated by several wells, which encountered a variable occurrence and thickness (from 120 m up to 2300 m) across the Wairakei-Tauhara Geothermal Field.

The Wairakei Ignimbrite is overlain by the **Waiora Formation**, a thick sequence of ignimbrite and volcanoclastic sedimentary deposits (intercalated crystal-lithic tuff and siltstones). The Formation is subdivided into five members (Wa 1 to 5). In places, the Waiora Formation is more than 2100 m thick, and hosts the main geothermal aquifers of the Wairakei geothermal system.

During the deposition of the Waiora Formation, a number of rhyolitic lavas and associated breccias were erupted, including the Poihipi Rhyolites, Karapiti Rhyolites and Te Mihi Rhyolites. Of these, the Karapiti-type rhyolites are the volumetrically greatest and hydrologically most significant. Although the Karapiti lavas are commonly devitrified and hydrothermally altered, they have been subdivided into **Karapiti 2A**, **Karapiti 2B** and **Karapiti 3 Rhyolite**. The Karapiti 2A Rhyolite is the thickest and most extensive rhyolite body at Wairakei, with an estimated 35km³ volume. The Karapiti rhyolites generally have good fracture permeability and can act as storage for low pressure steam. **Te Mihi Rhyolites** have only been intersected in peripheral wells near the western and eastern side of the Wairakei Field, and at Tauhara. **Poihipi Rhyolites** were described by Bignall et al. (2007), and are subdivided into the Poihipi 1 Rhyolite, Poihipi 2 Rhyolite and Poihipi Rhyolite Breccia.

Huka Falls Formation are lacustrine sediments and water deposited tuffs, and lie on top of the Waiora Formation. The unit is subdivided into Lower, Middle and Upper units. Huka Falls Formation has generally low permeability and acts as caprock (aquiclude) for the hydrothermal reservoir.

Deposits from the catastrophic Taupo eruption of about 26, 500 years ago are termed as **Oruanui Formation**. The formation comprises several pyroclastic units, interbedded with ash tuff of airfall and/or flow origin. The sequence is up to 170 m thick, and is commonly exposed at the surface.

3.1.2 Hydrothermal alteration

Subsurface rocks at Wairakei exhibit hydrothermal alteration of argillic and (generally with increasing depth) propylitic rank. Hot fluids pass through the reservoir rocks and change their mineralogy by adding, removing or redistributing components. Secondary minerals can replace primary mineralogy, or grow into open space.

The argillic hydrothermal assemblage may comprise smectite, illite, calcite and pyrite and is generally associated with low temperature conditions (< 230°C), and may occur under atmospheric conditions. Argillic-type alteration commonly affects the Oruanui and Huka Falls Formation.

Propylitic alteration typically occurs below the shallower argillic zone, and temperatures in excess of 240-260°C. Propylitic alteration commonly affects the deeper Waiora Formation strata and rhyolite lavas, and comprises a typical alteration assemblage of chlorite, quartz, epidote, albite, adularia, plus wairakite and titanite.

3.2 Field Hydrogeology

The Wairakei geothermal system is characterised by enhanced horizontal permeability. Currently, most of the major production zones are located within the layered pumiceous breccias of the Waiora Formation, and assorted rhyolites, shallower than ~1200 m vertical depth (although permeable zones have been intersected at various levels). Conceptual hydrogeological models suggest an upward flow of high-temperature, high-chloride fluid occurs at Te Mihi, with a sub-horizontal fluid flow through the mid-Huka Falls aquifer into the Western and Eastern Borefields. Major NE-trending faults cutting through the field also play a role in focussing fluid flow. A high permeable zone also exists in the SW part of the field, in Karapiti 2A Rhyolite, which influences fluid flow to the surface at Karapiti.

4. SAMPLES

In this study, most samples were taken from wells in the Te Mihi (western) part of the Wairakei Geothermal Field. Samples were selected only from the Waiora Formation, Karapiti Rhyolites and the Huka Falls Formation.

The effect of hydrothermal alteration on permeability and thermal conductivity was tested by analysing hydrothermally altered samples from the Te Mihi borefield, and least altered samples from the same stratigraphic units in wells at the field margin. Samples were collected from wells WK206, WK207, WK212, WK219 and WK247 (intensely hydrothermally altered Te Mihi upflow zone); WK223, WK224 and WK227 (near/outside the resistivity boundary zone at Wairakei); and from locations south and east of Te Mihi (WKM14, WK205, WK210, WK213, WK221 and one surface sample), as shown in Figure 4.

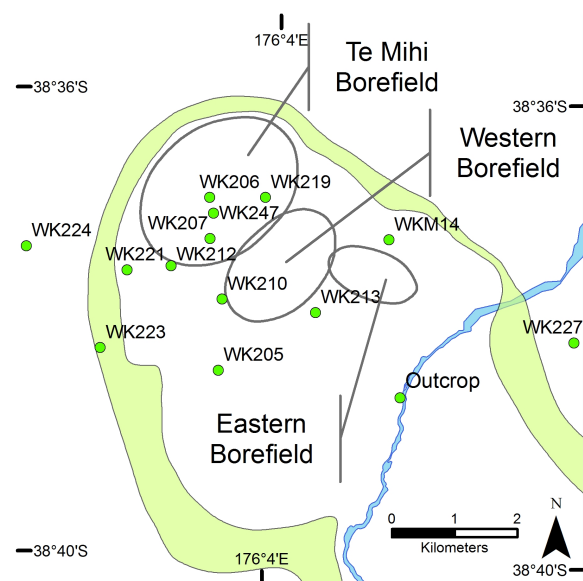


Figure 4: The Wairakei Geothermal Field, with sample well/outcrop locations indicated. The pale green area is the electrical resistivity (field) boundary.

4.1 Description

Samples were first examined in hand specimen and by thin section microscopy, and were classified into three lithological groups: a) mud dominated rocks; b) silt- and sand dominated rocks; and c) glassy rhyolitic lavas.

a. The first group comprises rocks with a homogeneous, clay-dominated groundmass. It includes seven mudstones of Huka Falls Formation, and one intensely hydrothermally

core sample from the Karapiti 2A Rhyolite and Waiora Formation. The mudstones are matrix-supported, with few lithics. Three samples are brecciated.

b. The second group comprises rocks of the Waiora Formation (fourteen samples) and Karapiti Rhyolites (six samples). The Waiora samples are tuffaceous silt to fine-grained sandstones, with varying amounts of lithics up to a few centimeters diameter. The Karapiti Rhyolites initially had a glassy groundmass, however intense hydrothermal alteration has devitrified the glass and left a set of secondary minerals similar to that in the Waiora Formation samples.

c. The third group comprises three Karapiti Rhyolites. These samples retain their glassy groundmass, and are considerably less devitrified than lavas of the second group.

XRD analysis confirmed that the moderate to intense hydrothermal alteration had produced a similar secondary mineral assemblage in each stratigraphic unit, comprising an argillic-style mineral assemblage of abundant illite-smectite, minor to abundant chlorite, and accessory quartz.

5. RESULTS

In general, thermal conductivity correlates poorly with permeability. All samples measured in this study were oven-dry, and we estimated a negative correlation between thermal conductivity and permeability. However, our data did not support that assumption. It seems grain to grain contact in the high permeable rocks is sufficient to sustain thermal conductivity. Huka Falls Formation samples had the lowest thermal conductivity (0.3 to 0.7 W/(m K)), while Karapiti Rhyolites and Waiora Formation samples have a thermal conductivity up to 1.9 W/(m K)).

We could not identify a consistent correlation between thermal conductivity and permeability within the respective stratigraphic units. Similarly, no dependency on sampling location could be inferred (Figure 5).

Whilst thermal conductivity and permeability data plot in point clusters, no consistent trends based on rock type/unit are revealed. Mud-dominated rocks have a constant low thermal conductivity that generally ranges between 0.3 and 0.9 W/(m K), with commonly permeabilities of $\sim 7\text{E}-16$ to $3\text{E}-14$ m². Silty rocks have a considerably higher range of permeability ($1\text{E}-17$ to $2\text{E}-14$ m²), and higher thermal conductivity (~ 0.6 to 1.6 W/(m K)). Glassy rocks generally have the highest thermal conductivity (~ 1.1 to 1.9 W/(m K)), and permeabilities of $5\text{E}-17$ to $1\text{E}-14$ m².

Figure 6 shows a permeability - thermal conductivity plot, based by lithology/textural type, with the cluster of Huka Falls Formation and Waiora Formation data seen in Figure 5 (green and red symbols) again evident. Hydrothermal alteration did not affect the texture of either stratigraphic units, but did enrich the clay component in a few Waiora Formation samples, which plot amongst the Huka Falls Formation mudstone group in Figure 6. For the most part, however, Huka Falls Formation (mudstone) and Waiora Formation (siltstone) samples can be differentiated.

By contrast, Karapiti Rhyolites appear to be subject to significant textural variability as a consequence of primary processes and hydrothermal alteration. In Figure 5, data for the Karapiti Rhyolites (blue symbols) are widely scattered, which highlight a heterogeneity of their physical properties. This can also be observed in Figure 6, where most Karapiti Rhyolite samples plot amongst the siltstone samples. Few

of the Karapiti Rhyolite samples are weakly altered, and/or retain much of their primary glassy, volcanic texture. The plots of permeability vs. thermal conductivity data reflect these textural differences. Intensely altered Karapiti Rhyolite samples are found to have similar permeabilities and thermal conductivities as “original” mud and siltstones, whereas least altered rhyolites (i.e. the glassy rock group) generally have higher measured thermal conductivities.

We also tested the relationship between thermal conductivity and dry porosity, which point to a moderate negative correlation between the two physical parameters (Figure 7). Mudstones generally have porosities of 35 to 50%, and siltstones 25 to 45%. Glassy rocks (i.e. least altered Karapiti Rhyolites) deviate from the correlative trend, but data are insufficient to make detailed inferences.

Figure 8 shows permeability and thermal conductivity data for samples from the Wairakei Geothermal Field, and for

samples from Central Europe. Similar stratigraphic types generally plot in a cluster, with no obvious relationship to other rock units. Samples from Wairakei have lower thermal conductivity than most of the other tested rocks, although some phyllites, clay and silt shale plot near the Wairakei samples. The permeability of samples from the Huka Falls and Waiora Formations are generally lower than other sandstones (e.g. Buntsandstein and Rotliegend Formations), but have generally higher values than clay and silt shale, gabbro or quartzite.

To some degree, the permeability and thermal conductivity of samples from the Huka Falls and Waiora Formations reflect their constituent mixture of clay and siltstone, and varying amount of fine sand. Quartzites have permeabilities that approximate values for the Karapiti Rhyolites, albeit with thermal conductivities about four times higher than measured in Karapiti Rhyolite samples.

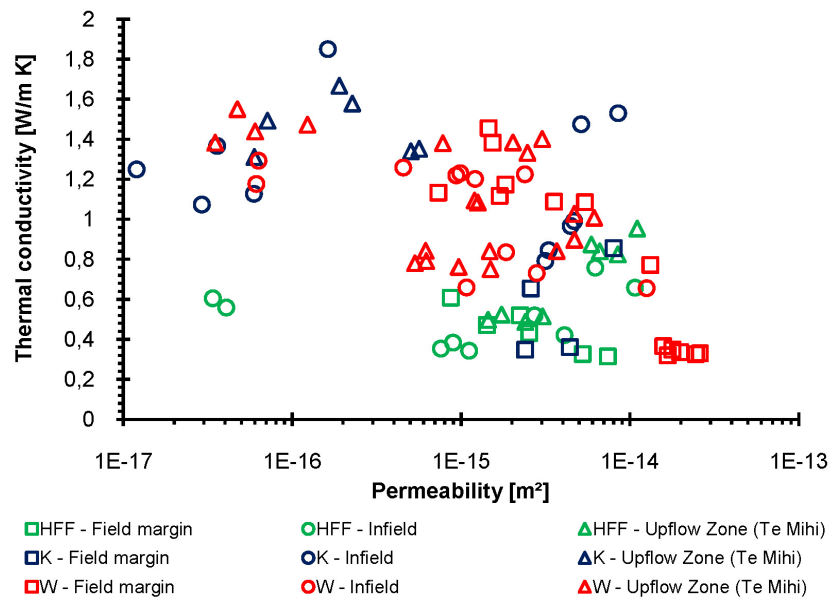


Figure 5: Plot of permeability vs. thermal conductivity data for Huka Falls Formation (HFF), Karapiti Rhyolites (K) and Waiora Formation (W), based on location within Wairakei geothermal system.

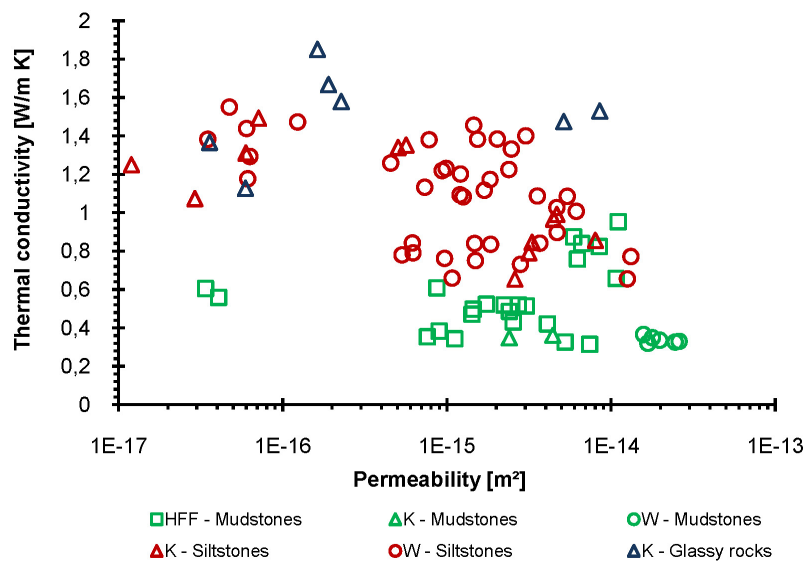


Figure 6: Plot of permeability vs thermal conductivity data for Huka Falls Formation (HFF), Karapiti Rhyolites (K) and Waiora Formation (W), based on lithological and textural character of samples.

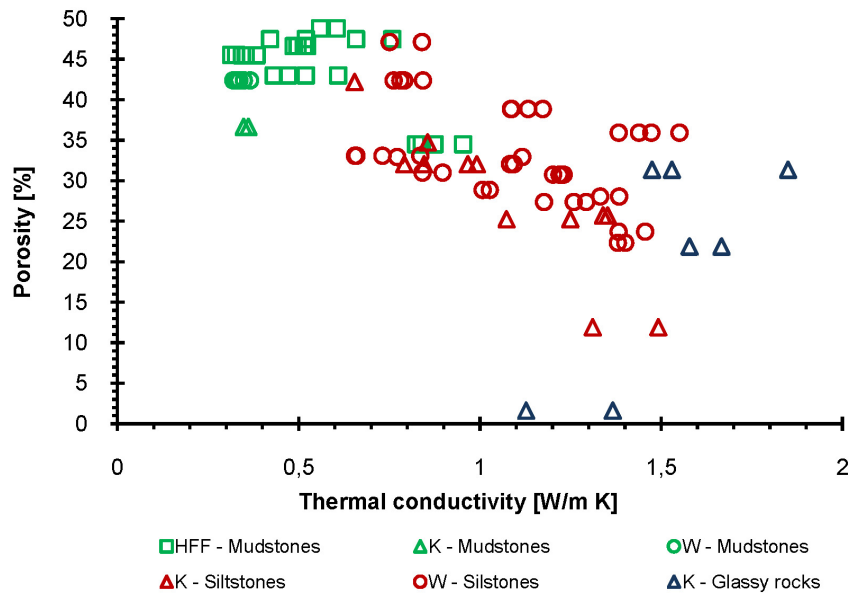


Figure 7: Plot of thermal conductivity vs. porosity data for Wairakei core samples (this study), showing a negative correlation for mud and siltstones.

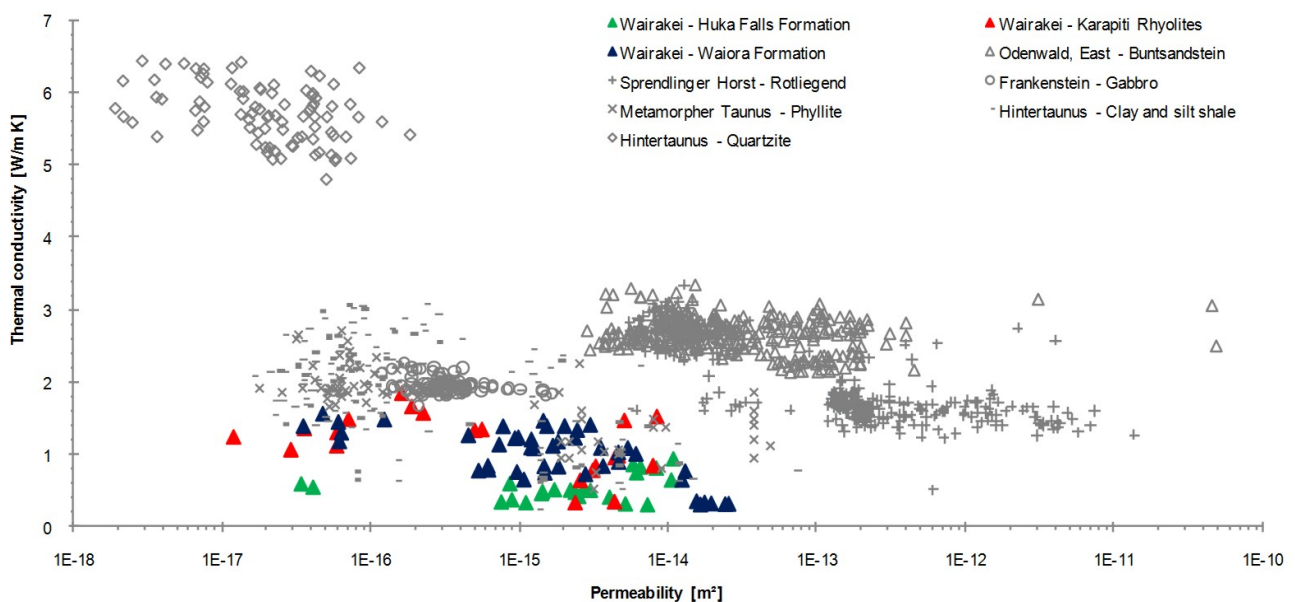


Figure 8: Plot of permeability vs. thermal conductivity for samples from the Wairakei Geothermal Field (this study), and various stratigraphic units/locations in Central Europe (from Sass and Buß, 2007; Sass et al., 2008). The figure shows sandstones generally have high permeabilities and thermal conductivities, while clay and silt dominated shales and phyllites have lower permeabilities, but thermal conductivities similar to the sandstone.

5. CONCLUSIONS

Core samples of Huka Falls Formation, Waiora Formation and Karapiti Rhyolite from the Wairakei Geothermal Field have permeabilities of $1\text{E-}17$ to $3\text{E-}14$ m^2 , and thermal conductivities of 0.3 to 1.8 $\text{W}/(\text{m K})$. No correlation is established between the two rock property parameters.

Mud-dominated rocks from the Huka Falls Formation have the lowest thermal conductivity of 0.3 to 0.9 $\text{W}/(\text{m K})$ and permeabilities of $7\text{E-}16$ to $3\text{E-}14$ m^2 . Siltstones from the Waiora Formation, and Karapiti Rhyolites have a similar permeability as the mudstones, but higher thermal conductivities (~ 0.6 to 1.6 $\text{W}/(\text{m K})$). Glassy rhyolites have the highest thermal conductivity (about 1.1 to 1.9 W/m).

Hydrothermal alteration affected the Karapiti Rhyolites, by destroying its glassy groundmass, and reducing its thermal conductivity. We infer the transformation from a glassy to crystallised state caused an increase of boundary effects, which impacts heat flow. More investigations are necessary to test this assumption.

In this study we also investigated the effect of porosity on the thermal conductivity, and found a moderate negative correlation, particularly for core samples from the Huka Falls and Waiora Formations. We infer hydrothermal alteration has enhanced porosity, possibly due to the replacement of primary minerals and groundmass/matrix, although permeability was reduced due to the development

of a low permeable (clay-rich) matrix. Work is ongoing, to test this, and other hypotheses.

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