PREDICTING THE EFFECT OF HYDROTHERMAL ALTERATION ON ROCK PROPERTIES

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ABSTRACT

Hydrothermal alteration records physicochemical changes to a rock, including dissolution and/or precipitation of new mineral phases, by its interaction with hot mineralised fluid. Transient geochemical processes can alter thermo-physical and thermo-physical rock properties. The prognosis and quantification of hydrothermal alteration processes in reservoir rock properties is crucial to enhance the ability of THM reservoir models. To predict the effect of hydrothermal alteration on rock properties a database detailing hydrothermal alteration, matrix permeability, porosity, rock strength and thermo-physical parameters (e.g. thermal conductivity, heat capacity) has been established for various volcanic rock types. The database includes data from a) ~450 drill cores from hydrothermally altered volcaniclastic, sediments and lavas from wells THM12, THM13, THM14, THM17, THM18, THM19 and TH18 in the Tauhara Geothermal System, and b) from outcrop analogue studies of fresh and altered volcaniclastics and lavas throughout the Taupo Volcanic Zone and Coromandel Volcanic Zone. Thermo-physical rock properties have been determined by applying a combination of new and existing methods. New methods include a mobile permeameter and thermal conductivity scanner, a hydrothermal triaxial device and µ-computer-tomography. Standard tools include X-ray fluorescence, shortwave infrared analysis, optical microscopy, clay mineral characterisation and gas porosity.

1. INTRODUCTION

This paper reports preliminary results from a large-scale outcrop and drill core analogue study in the North Island of New Zealand. The study has been set up to investigate the thermo-physcial rock properties of deep geothermal reservoir rocks at the present situation, and furthermore to predict the effect of natural and artificial hydrothermal alteration on thermo-physcial rock properties.

Most geothermal reservoirs are located in active volcanic settings, where hot, mineralized deep water and steam is captured in permeable reservoir rocks beneath an impermeable cap rock. The prevailing physico-chemical conditions in the system are often unstable, which can be of natural or artificial cause, e.g. pressure and temperature changes and associated new fluid paths due to production, or the infiltration of fluids with varying hydro-chemical composition. These transient physico-chemical conditions cause a disequilibrium between the mineral assemblage of the host rock and the circulating fluids, leading to re-equilibration of the system by the formation of new secondary mineral assemblages that are stable under the new conditions. The secondary mineralization can alter the thermo-physical rock properties (e.g. porosity, density, rock strength, thermal conductivity, heat capacity), which in turn can significantly impact the reservoir exploitation and development (e.g. clogging of fluid paths by precipitated secondary minerals, or subsidence anomalies due to softened rocks). Hence, it is of essential interest for the geothermal industry to a) know the physical and mechanical rock properties of the host rocks (e.g. to improve the drilling performance and efficiency); and b) to predict the effect of changing physico-chemical conditions on rock properties for better reservoir management and long term predictions of the reservoir productivity.

Consequently, if the thermo-physical properties of a specific rock type of interest are known (e.g. from outcrop or drill core analogue studies) and, furthermore, the effects of hydrothermal alteration on these rock properties are known, the rock properties of the (altered) reservoir rocks at depth could be predicted. Furthermore, the change of rock properties with ongoing hydrothermal alteration due to (artificially?) changed physic-chemical system conditions can be prognosticated, e.g. for numerical models.

Hydrothermal alteration and the geochemical mechanisms that cause secondary mineralization have been described by many authors (Barnes, 1997; Giggenbach, 1981; Browne, 1978). The alteration type can be determined by a range of petrological and geochemical techniques that often require little quantities of sample material, which can for example easily be obtained from drill cuttings. Many experimental studies led to the development of thermodynamic databases, which facilitate the modelling of mineral phases at given physico-chemical conditions (e.g. Bethke, 2008).

By contrast, the requirements for the investigation of thermo-physical rock properties are much higher. Sample need to be undisturbed and intact, and the dimensions need to be larger. These entire requirements can commonly only be achieved by expensive core recoveries from deep wells in the geothermal systems. Thus, the ability for measuring and/or predicting thermo-physical rock properties and, in a next step, the effect of hydrothermal alteration on them, is often limited by the number of suitable wells and the lack of intact core material. Hence, studies of this kind on cores from geothermal systems are rare. Studies in geothermal fields in New Zealand were published by Siratovich et al. (2014) and Wyering et al. (2013), who investigated rock-strength, ultrasonic wave velocities and porosity of andesite cores from geothermal wells in Ngatamariki, Rotokawa and Kawerau. Kristinsdóttir et al. (2010) and Jaya et al. (2010) investigated the temperature dependency of the sonic velocity of volcanic rock samples from Iceland.

Previous works that tried to link hydrothermal alteration and thermo-physical rock properties typically focus on specific formations or drill holes. Wyering et al. (2013) linked hydrothermal alteration and mechanical data of andesites from geothermal fields in New Zealand. Porosity and permeability data of altered volcaniclastic rocks has been published by

Dobson et al. (2003) for wells in the Yellowstone geothermal system (U.S.A), by Lenhardt and Götz (2011) for the Tepoztlán Formation in Central Mexico, and by Stimac et al. (2004) for the Tiwi geothermal field in the Philippines. Pola et al. (2012) published porosity and ultrasonic velocities of tuffs from Solfatara, Bolsena, and Ischia (Italy) and linked the data to a range of alteration indices.

The limitations of core studies can be overcome by outcrop and drill core analogue studies, which have proven to be effective in predicting fundamental geothermal reservoir properties. Tens of thousands outcrop data of fresh and altered rocks is available to collect, with the advantage of high accuracy of statistical data. High population numbers provide confidence in applying this statistical data to geothermal models of the deep reservoir. Götz et al. (2014) applied this concept for studying the Meso- and Cenozoic carbonates and siliciclastics in the region of Budapest, Hungary. Homuth et al. (2014) investigated carbonates from the Upper Jurassic in Southern Germany and demonstrated the relationship between thermo-physical rock properties and diagenesis. Bär et al. (2011) and Bär and Sass (2014) studied the potential of sedimentary rocks of the Rotliegend in the Upper Rhine Valley, while Aretz et al. (2013) studied the geothermal reservoir potential of the Permocarboniferous in the northern Upper Rhine Graben.

The disadvantage of outcrop data is the lack of opportunities to measure the effect of reservoir conditions (i.e. elevated temperature and pressure) on rock properties. By analysing the thermo-physical rock properties of rocks from outcrops and/or wells under elevated temperature and pressure, the in-situ rock properties can be inferred. Furthermore, by incorporating artificial hydrothermal alteration of reservoir rocks in high temperature pressure apparatus to simulate fluid-rock interactions in a deep reservoir, the effect of hydrothermal alteration on thermo-physical rock properties in the deeper reservoir can be predicted. The results of such studies can be applied in thermofacies concepts (Sass and Götz, 2012). Recent laboratory tests by Homuth et al. (2014) dealing with the prediction of permeability and rock strength parameters under reservoir stress conditions, or experimental fluid-rock interactions have proven the feasibility of such research.

2. METHODOLOGY

This study focuses on investigating the effect of hydrothermal alteration on thermo-physical rock properties in a large-scale outcrop and core analogue study. Hundreds to thousands samples of fresh and hydrothermally altered rock are taken at various locations in New Zealand. The hydrothermal alteration rank and intensity of each sample is examined, and the thermo-physical rock properties are measured. The effect of hydrothermal alteration on rock properties is investigated by selecting rock formations that exhibit a range of differing alteration ranks and intensities. Furthermore, fresh samples are artificially altered in high temperature and pressure devices, while the gradual change of the rock properties is logged continuously, or compared before and after each test.

2.1 Samples

Rock samples for this study derive from outcrops and wells in the Taupo Volcanic Zone and the Coromandel Volcanic Zone in New Zealand. To date, rock sampling has not been finished and is ongoing process.

More than 450 plugs have been cut from cores drilled a wells THM12, THM13, THM14, THM17, THM18, THM19 and TH18 from the Tauhara Geothermal Field, with depths ranging from 289 m to 878 m (Figure 1). The depth intervals studied cover the volcaniclastic deposits of the Upper (UHF), Middle (MHF) and Lower Huka Falls Formation (LHF), which are formed by a mixture of layered sediments, breccias and tuffs that act as an aquitard separating hot fluids in underlying permeable zones of the underlying Waiora Formation from cool overlying groundwaters; Waiora Formation (WAI), which consists of a varied sequence of volcanic deposits, with interlayered mudstones, siltstones and sandstones that hosts the main geothermal aquifers; and associated intrusive rhyolite (Racetrack Rhyolite, RR) and andesite (SPA Andesite, SPA) domes. The geology of the Tauhara Geothermal Field has been discussed in numerous publications, including Bromley et al. (2010) and Rosenberg et al. (2009a, 2009b, 2010). Hydrothermal alteration is typically of argillic and propylitic type with intensities ranging from low to high.

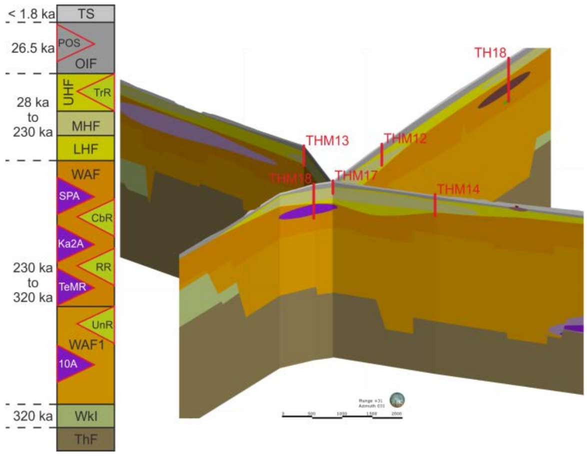

Figure 1: Simplified stratigraphic table and cross section through some of the sampled wells.

Outcrop analogue studies have so far been conducted in quarries and outcrops in the Taupo Volcanic Zone and Coromandel Volcanic Zone, where 60 cores have been drilled. Unaltered andesite was sampled at Waihi Village (Taupo), slighly altered andesite at Poplar Lane quarry (Tauranga), and fresh to intensely altered andesite at outcrops at Karangahake Gorge (Kaimai Ranges). Rhyolites were sampled at a quarry in Rotorua, and dacite at a quarry in Tauhara (Taupo).

A detailed study of a single andesite formation was conducted at Karangahake Gorge, where a large andesite body exhibits a range of hydrothermal alteration intensities from weakly to highly altered along a ~1.5 km wide outcrop, thus offering a perfect opportunity to measure the effects of hydrothermal alteration on rock properties. Here, 85 samples have been collected in intervals of ~8 m.

2.2 Measurement methods

In contrast to most geochemical and mineralogical investigations, most thermo-physical measurements require an intact sample with specific shapes and dimensions. In this study, most measurements were and will be done with plugs drilled from boulders or larger drill cores. The diameter is either 2 cm or 4 cm, the thickness ranges from 2 cm to 4 cm. For uniaxial and triaxial test drill cores with a diameter of 6.5 cm and a length of 13 cm are used. Where possible, anistropic properties are measured by drilling the plugs and cores in horizontal and vertical direction to the anisotropy (e.g. layering, bedding, flow-banding). All tests are done on oven-dried samples, which are dried in a conventional laboratory oven for at least 48 h at 40 °C and subsequently cooled down to room temperature.

Petrology and hydrothermal alteration is determined using reflective light microscopy, Methylene Blue Dye Absorption (MBT) test, short wave infrared spectroscopy (SWIR), and x-ray fluorescence. With the exception of the MBT test, all tests are done on the intact surfaces of sample plugs or cores.

Routinely measured thermo-physical rock properties encompass porosity, bulk and grain density, permeability, thermal conductivity and specific heat capacity.

Additional tests for selected samples include P- and S-wave velocity, uniaxial, and triaxial tests. A special triaxial test device capable of simulating reservoir conditions is used to a) measure permeability, porosity and rock strength at various elevated temperatures and pressures and b) to artificially increase the hydrothermal alteration rank and intensity of fresh rock samples by circulating artificial brines through the matrix to observe the change of the thermo-physical rock properties. Induced changes of the pore space and recrystallized mineral phases are visualized and computed using X-ray computed microtomography and environmental scanning electron microscopy.

2.2.1 Methylene Blue Dye Absorption

The MBT is used to estimate the amount of swelling clays, which in this geological setting comprise to a large extend of smectite. The test determines the adsorption capacity of Methylene Blue (an organic dye) by smectite clays and the smectite component of mixed-layer clays. Thus, the amount of smectite can be estimated on a semi-quantitative basis (c.f. Gunderson et al. 2010) by measuring the amount of adsorbed dye. The MBT is the only test which had not been carried out on intact plugs but on crushed cuttings obtained during the drilling of the plugs.

2.2.2 Short wave infrared spectroscopy and X-ray fluorescence

SWIR is carried out using a commercial TerraSpec 4 Hi-Res Mineral Spectrometer from ASD Inc. The device allows rapid and cost-effective qualitative clay mineral identification and, furthermore, can be used to determine illite crystallinity and general chemistry of chlorite and carbonates based on the relative intensity or wavelength position of specific absorption features (c.f. Herrmann et al. 2001; Jones et al. 2005). By calculating the H2O / AlOH ratios from both reflectance (raw) and hull quotient corrected spectra, smectite, interstratified illite-smectite and illite can be distinguished (Figure 4). In general, samples with a hull quotient corrected H2O / AlOH ratios of >0.96 correspond to illite, and <0.76 corresponds to smectite and values between 0.76 and 0.96 encompass most interstratified illite-smectite (c.f. Simpson et al. 2013).

X-ray fluoresce is carried out with different portable and stationary device located at labs in New Zealand and Germany.

2.2.3 Density and porosity

Bulk and grain density are measured using a commercial gas-driven pycnometer (Micromeritics AccuPyc) combined with a displacement measuring technique (GeoPyc) that utilizes a fine-grained powder as quasi-fluid for the determination of the sample volume. Both values are used to calculate the porosity. The method allows fast but highly accurate measurements of high quantities of samples. Returned values represent the gas-effective porosity.

2.2.4 Permeability

Gas-permeability is measured using a combined columnar and mini permeameter. The columnar permeameter allows permeability measurements of entire core plug samples under steady-state gas flow (ASTM D4525, 2013). The minipermeameter is used for point-wise measurements on plane or curved surfaces. Gas-driven permeability measurements have the advantage of not contaminating the sample with fluids and not affect clay-bearing samples, which may swell when tested with fluid and alter the sample. Both methods are capable of measuring permeability ranging from 6 d to 1 µd. The device has been verified by Filomena et al. (2013). Gas-permeability values of selected samples are compared with water-permeability values obtained in the thermal-triaxial test device, see paragraph 2.2.9.

2.2.5 Thermal conductivity and volumetric heat capacity

Thermal conductivity and thermal diffusivity is measured using a Lambda Measuring Center (LMC) from Geotechnical Technology Hamm & Theusner GbR and a Thermal Conductivity Scanner (TCS) from Lippmann & Rauen GbR (Figure 2). Both devices evaluate the thermal conductivity and thermal diffusivity using the optical scanning method of Popov et al. (1999). While the LMC is used to measure the thermal properties of plugs, the TCS is used to measure sections along core samples. Temperature sensors measure the initial temperature of the specimen. Subsequently, an infrared emitter heats up the specimen for a defined time (commonly few seconds). After a defined cooling time the temperature is measured again and the difference is evaluated. Finally, the thermal conductivity is calculated from the temperature difference and by comparison with the readings from known standards. The thermal diffusivity of the sample is calculated in a similar way, with the exception that the temperature difference is measured in a given distance from the heating spot. Both, thermal conductivity and thermal diffusivity are used to calculate the specific heat capacity can by incorporating the bulk density.

Figure 2: Thermal Conductivity Scanner with two rock samples and two standards made of fused glass.

2.2.6 P- and S-wave velocity

Ultrasonic sound velocity is measured with a commercial Geotron Ultrasonic generator USG 40 with a frequency of 80 kHz. Plugs and cores are measured in horizontal and radial direction. The resulting S- and P-wave velocities are used to calculate Young's moduls and Poisson's ratio, both properties are later validated in uniaxial and triaxial shear tests.

2.2.7 Rock strength

Uniaxial rock strength is tested using a commercial uniaxial test rig manufactured by Wille Geotechnik. Specimens are loaded axially up to failure or any other prescribed level whereby the specimen is deformed or breaks and the axial deformation can be measured (ASTM D7012, 2014).

2.2.8 Thermal-triaxial test device

The thermal-triaxial test device (Thermo-Triax, Figure 3) is a modified triaxial test rig capable of simulating hydrothermal reservoir conditions temperatures up to 180°C, loading stress up to 400 MPa and confining pressure up to 50 MPa, while tempered fluids percolate through the rock matrix or fissures. Specimens have to be cylindrical, intact, with a diameter of 64 mm and a height of max. 150 mm. Compressibility and permeability can be obtained under a range of operating (simulation reservoir) conditions, in series of multiple week or month-long experiments that will monitor changes in permeability and rock strength accompanying advancing hydrothermal alteration intensity caused by the hot brine interacting with the rock matrix.

Figure 3: The Thermo-Triax test rig.

2.2.9 X-ray computed microtomography and environmental scanning electron microscopy

Computed X-ray microtomography (µ-CT) is carried out using a Procon X-Ray CT-Alpha commercial instrument at the Institute for Geosciences, Johannes Gutenberg University, Germany. The method facilitates the visualization and computation of changes of the pore space caused due to artificial hydrothermal alteration in high temperature and pressure experiments conducted with the Thermo-Triax.

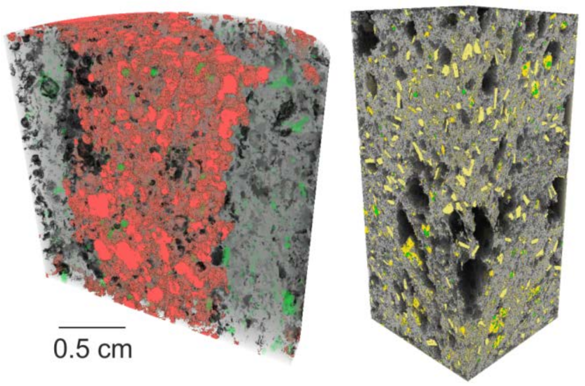

Figure 4: µ-CT scan of a flow-banded rhyolite (left) with connected pore space (red), isolated pores (black), minerals (green) and matrix (transparent grey); and andesitic tuff (right) with pore space (black), feldspar (yellow) and matrix (grey).

3. PRELIMINARY RESULTS

Rock sampling and laboratory tests are still in progress, thus only preliminary results are presented here.

Figure 5 shows exemplary results from well THM18 at the Tauhara Geothermal Field. Samples have been classified by lithology into volcaniclastic deposits (ash and lapilli tuff), sedimentary deposits (sandstone, siltstone and mudstone) and intrusive andesite and rhyolite lavas and their associated breccias. Figure 6 plots permeability and thermal conductivity vs. porosity (Figure 6). Lithology classes typically plot in point clusters.

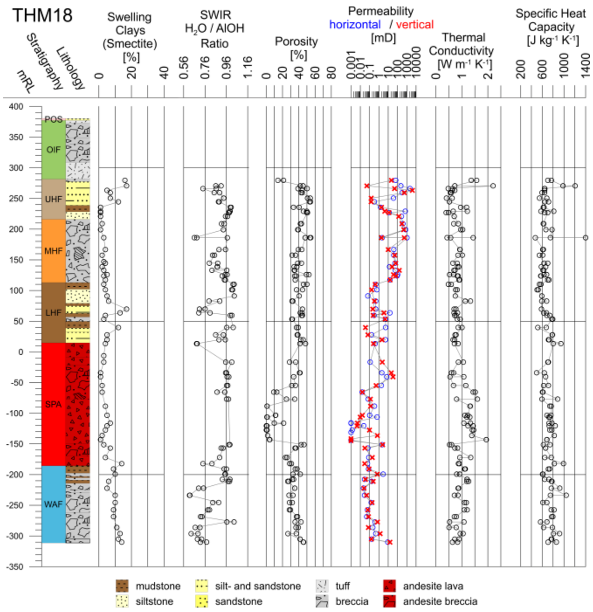

Figure 5: Thermo-physical data from well THM18.

The average porosity of volcaniclastic and sedimentary rocks generally ranges between 30% and 50%. Andesite, rhyolite lava and breccia have 10% to 20% lower porosities. Permeability of sedimentary classes increases with grain size. Permeability of rhyolite and andesite lava differs in more than two orders of magnitude, lava breccias differ up to three orders of magnitude.

Thermal conductivity correlates with porosity and decreases with increasing porosity due to the low thermal conductivity of air (~0.026 W m^{-1} K^{-1} at 20 °C) in the pore space. Thermal conductivity typically increases with porosity and is independent from permeability. Ash and lapilli tuff, and sedimentary samples typically have thermal conductivities below 1 W m^{-1} K^{-1}, while the lavas have thermal conductivities up to 1.5 W m^{-1} K^{-1}. Furthermore, thermal conductivity is affected by grain size (Figure 6, upper chart, magnification). Finer grained samples (i.e. siltstone and mudstone) have slightly higher thermal conductivities than coarser samples (i.e. sandstones), although they have the same porosity.

The combination of hydrothermal alteration with porosity, permeability and thermal conductivity data hints at a controlling effect of alteration on rock properties. Hydrothermal alteration in this setting is commonly of argillic type, as indicated by the replacement of minerals and volcanic glass with fine-grained clays, typically smectite, illite, and/or their mixtures. In general, the occurrence of secondary clay increases with depth. By combining MBT and SWIR data (Figure 5, logs “Swelling Clays” and “SWIR”) and microscopic analysis the alteration style and intensity can be estimated. However, more sophisticated analysis are required (e.g. from XRF studies) for a better qualification and quantification of the hydrothermal alteration, and the calculation of alteration indices.

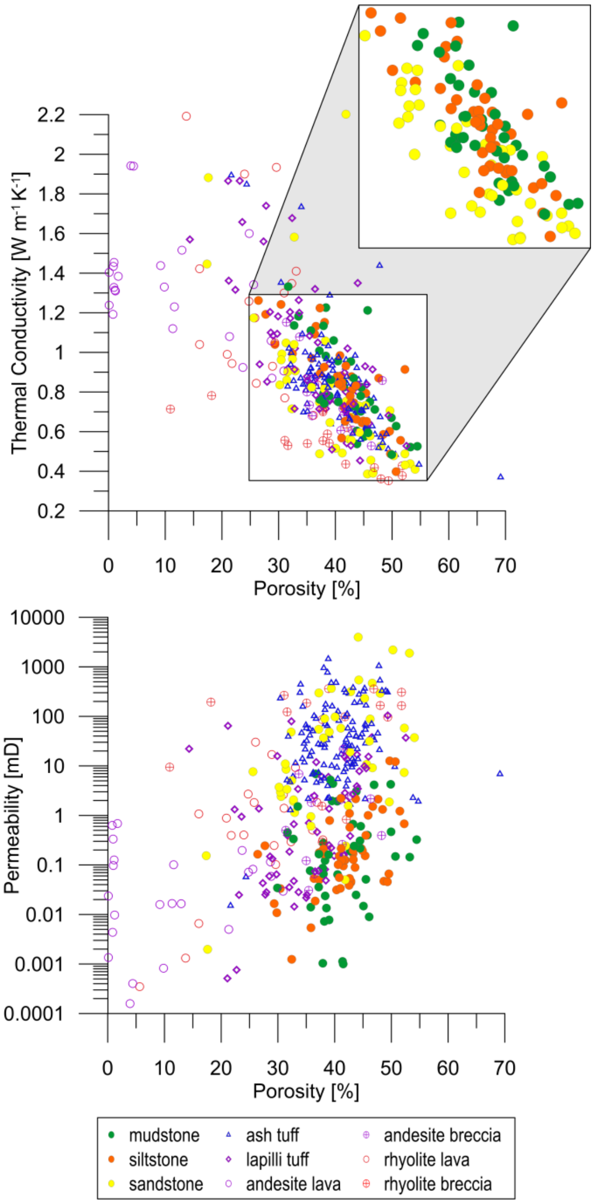

Figure 6: Cross plots of thermal conductivity and permeability vs. porosity.

The impact of hydrothermal alteration on rock properties is exemplarily shown in Figure 7 for ash tuff samples from Tauhara. Samples are classified by their hydrothermal alteration intensity from weak to high. Weakly altered ash tuff has among the highest permeability and porosity. With increasing alteration intensity to moderate permeability decreases up to one order of magnitude, while porosity remains stable. By contrast, with advancing alteration to high intensity the permeability slightly increases again up to a level comparable to weakly altered samples, while porosity decreases by ~10% (excluding outliners). In general, the size of the point clusters of each alteration class increase with advancing alteration, hinting towards an increasing heterogeneity of the rock textures, caused by the re-crystallization of primary minerals.

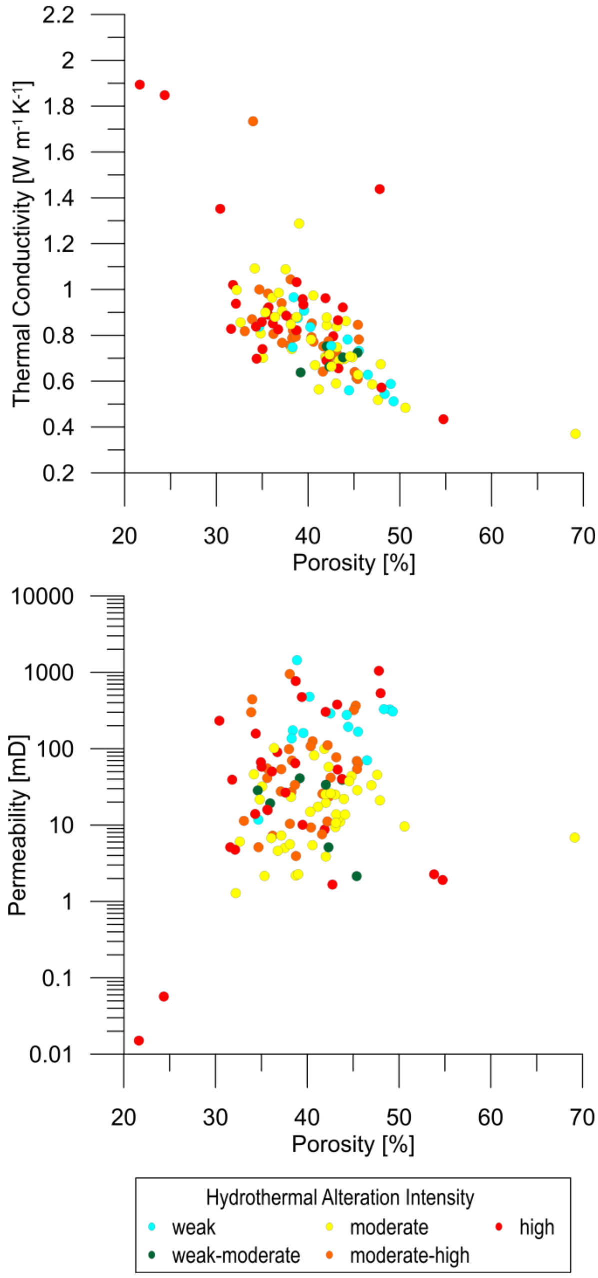

Figure 7: Hydrothermal alteration and thermo-physical rock properties of ash tuff from Tauhara.

The effect of alteration on thermal conductivity is less complex. Thermal conductivity generally increases with alteration intensity (weakly altered samples: ~0.7 W $m^{-1}K^{-1}$; highly altered: ~0.9 W $m^{-1}K^{-1}$), presumably due to the formation of denser, compacted minerals in the matrix and pore space.

The correlation of element quantities with thermal conductivity has been investigated in a detailed XRF and thermal conductivity study of altered andesite sampled in Karangahake Gorge, a fossil geothermal system in the Coromandel Volcanic Zone. The outcropping andesite exhibits increasing hydrothermal alteration intensity from weakly to highly altered. Samples have been collected in intervals of ~8 m. Hydrothermal alteration is nearly fresh on the north-western side of the outcrop (right side in Figure 8), and increases to high alteration in the south-east. Silicon (Si) increases with alteration due to the increasing silicification of the rock, while Aluminum (Al) decreases. With few exceptions of some trace elements all other elements remain stable. By contrast, and similar to the results obtained from the samples from Tauhara, thermal conductivity increases with alteration (and Si content).

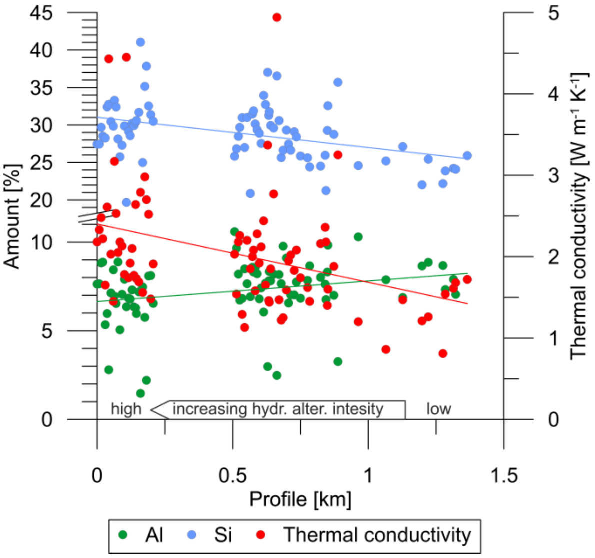

Figure 8: Al and Si concentrations and associated thermal conductivity of andesite samples along a ~1.5 km long outcrop in Karangahake Gorge.

Figure 9 shows the result of a long term permeability test of an andesite sample from Poplar Lane quarry. The sample was mounted into the Thermo-Triax with a vertical stress of 12 MPa and a confining pressure of 5 MPa. It was saturated for ~100 hours with a backpressure of 1.5 MPa. The permeability test was conducted with a backpressure of 3 MPa and a pressure gradient of 1 MPa. In the range of 30 °C to 125 °C permeability decreases with increasing temperature, probably due to the thermal expansion of crystals. A temperature increase to 170 °C did not further affect the permeability.

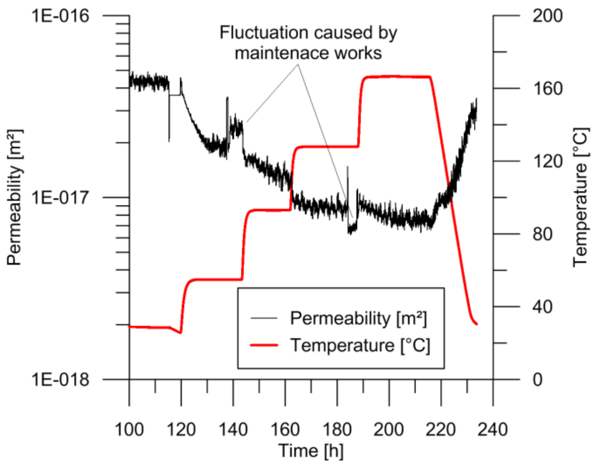

Figure 9: Permeability of an andesite from Poplar Lane at different temperatures.

3. CONCLUSION AND OUTLOOK

This paper presents preliminary results of a large-scale outcrop and core analogue study, which aims at developing a method to predict 1) the change of thermo-physical rock properties with depth and b) the effect of hydrothermal alteration on these rock properties.

First tests of altered rocks from the Tauhara Geothermal Field suggest increasing thermal conductivity with increasing alteration intensity. This result has been verified in a detailed outcrop analogue study of andesite that exhibits different alteration intensities in one rock formation.

Additional tests revealed a complex relationship between hydrothermal alteration and permeability. Test data of tuff exhibiting argillic alteration in a range of alteration intensities indicates that the matrix permeability is reduced by low to moderate alteration, but increases again with advancing alteration. Ongoing tests with other rock and alteration types have been started to verify these results.

In an accompanied study the distribution of elements in an andesite exhibiting advancing hydrothermal alteration from fresh to highly altered has been analyzed. First results point towards a correlation between the amount of Si and thermal conductivity. Correlations with other thermo-physical rock properties are currently under research.

In a next step, more samples of all rock types in question are being collected. XRF studies will be conducted with all samples to allow the calculation of alteration indices, which facilitates a better classification of hydrothermal alteration. Furthermore, the rock properties are evaluated in uniaxial and triaxial tests, partially under reservoir conditions.

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