

New methods of determining rock properties for geothermal reservoir characterization

Neue Methoden zur Bestimmung der Gesteinseigenschaften für eine geothermische Reservoircharakterisierung

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Abstract

The influence of hydrothermal alteration on permeability, thermal conductivity and thermal diffusivity was investigated for more than 300 drill cores from the wells THM18, TH18 and THM19 of the Tauhara Geothermal Field (Wairakei, New Zealand). The measurements were performed with newly developed, portable laboratory devices. The anisotropic, intrinsic permeability was measured with a gas pressure Columnar-Permeameter, while the thermal conductivity and thermal diffusivity were measured with a device based on the optical scanning method. The hydrothermal alteration rank (argillic or propylitic) was determined semi-quantitative by methylene blue dye adsorption tests in combination with thin section analyses for selected samples. Samples from the Huka Fall Formation (HFF) and the Waiora Formation (WAF), composed of layered mud-, silt- and sandstones as well as pumice-rich tuffs deposited in a limnic environment as well as the associated rhyolitic and andesitic intrusives were examined. An increasing amount of illite and the corresponding decrease of smectite indicate a prograde alteration with depth. Generally lithologies of higher primary permeabilities are more affected by hydrothermal alteration. With an increase of secondary clay minerals the permeability decreases.

Keywords: Hydrothermal alteration, thermal conductivity, permeability, methylene blue dye adsorption test

Zusammenfassung

An über 300 Bohrkernen aus den Bohrungen THM18, TH18 und THM19 im Tauhara Geothermiefeld (Wairakei, Neuseeland) wurde der Einfluss der hydrothermalen Alteration auf die Permeabilität, Wärmeleitfähigkeit und Temperaturleitfähigkeit mit neu entwickelten, transportablen Messgeräten untersucht. Die richtungsabhängige, intrinsische Permeabilität wurde mit einem Säulen-Permeameter ermittelt, während die Wärme- und Temperaturleitfähigkeit mit einem Messgerät, basierend auf der optischen Scan-Methode, ermittelt wurde. Der Grad der hydrothermalen Alteration (argillisch oder propylitisch) wurde semiquantitativ über den Gehalt an quellfähigen Tonmineralen mittels Methylenblau-Adsorptionstests bestimmt. Zusätzlich wurden Dünnschliffanalysen an ausgewählten Proben durchgeführt. Die Wechselfolgen von Tuff-, Asche- und Brekzienablagerungen mit Einschaltungen andesitischer und rhyolitischer Laven zeigen eine prograde Alteration mit zunehmender Tiefe, sowie eine Abhängigkeit der Alteration von der primären Permeabilität.

Schlüsselworte: Hydrothermale Alteration, Permeabilität, Wärmeleitfähigkeit, Methylenblau Adsorptionstes

1 Introduction

The Tauhara Geothermal Field situated next to the Wairakei Geothermal Field is part of the Taupo Volcanic Zone (TVZ). This zone is an active volcanic arc and back arc basin on the central North Island of New Zealand of Pliocene to Quaternary age (Cole 1990; Wilson et al. 1995). Numerous wells were already drilled and field conditions are geologically and mineralogically as well as chemically and physically well defined. The epithermal system is characterized by 300 °C hot water, which rises from a depth of 5 to 8 kilometres. Samples have been taken from well TH18, located at the resistivity boundary outside of the active geothermal area and from wells THM18 and THM19, which are situated within the centre of the Tauhara Field, close to the subsidence bowls (see figure 9). The wells are

fully cored with a diameter of 60 mm and the cores are specially preserved in foil. The samples were taken at intervals between 5 to 15 m depending on the heterogeneity of the respective stratigraphic formation.

Petrophysical measurements and petrographic characterization of the samples were used to evaluate the effects of lithology and hydrothermal alteration on permeability, thermal conductivity and thermal diffusivity. In order to explain the measurement results more accurately, the samples were classified by lithological criteria (e.g. texture, fabric, grain size, mineralogy). Eight distinct lithologies can be identified: silty mudstones, silty sandstones, pumice-rich crystal tuffs, sedimentary breccias, andesitic lavas, hydrothermal breccias within the andesite, rhyolitic lavas, rhyolitic breccias and mixed igneous breccias.

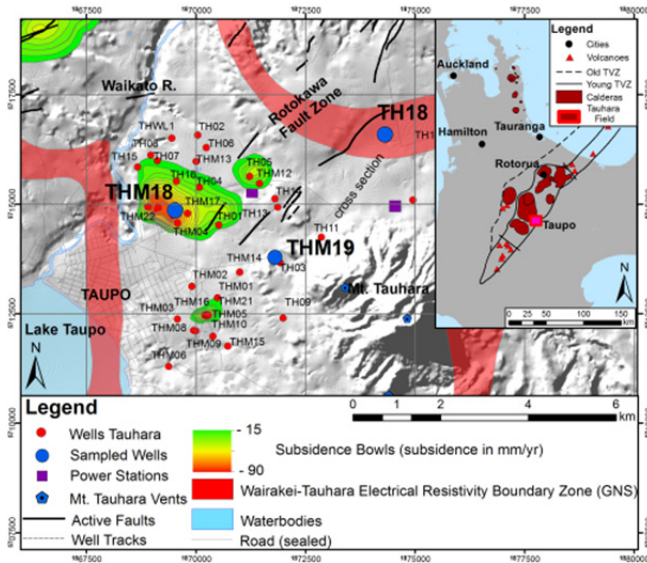


Fig. 9: Map of the Tauhara Geothermal Field with sampled wells marked by blue dots. Adapted and modified after Rosenberg et al. (2009).

Abb. 9: Karte des Tauhara Geothermiefelds mit beprobten Bohrungen markiert durch blaue Punkte. Illustration verändert nach Rosenberg et al (2009)

2 Sample preparation

The successive steps of sample preparation are shown in figure 10. Oriented plugs (vertical and horizontal) were drilled out of existing, specially preserved drill cores with a diameter of 60 mm. The cylindrical plugs must have a diameter of 40 mm and lengths between 30 and 45 mm for the measurements. To identify the bottom and top of the vertical samples, they were spray-colored with red and green enamel varnish on the side face. The alignment of the colors was specified for every sample in the same way. Furthermore, slices of around 2 cm thickness were cut for the preparation of oriented thin sections. The overcut material was ground to prepare approximately 4 g powder for the semi-quantitative methylene blue dye adsorption tests to identify the clay minerals. Afterwards the plugs were dried at 40 °C for 48 h.

Before starting the measurements with the Columnar-Permeameter, the top and bottom surface of the samples were polished with abrasive paper or a polishing machine to create parallel planes. For some samples, it was necessary to fill up holes and cracks with a kneadable, fast setting, epoxy material. For this purpose a two components polymers repair system was used. The kneadable mass could be moulded to shape and would adhere to the surface of the rock samples permanently. This has an effect on the permeability of the samples and has to be taken into account for the analysis. After measuring the samples with the Columnar-Permeameter, they were prepared for the measurements with the Lambda Measuring Center (LMC). Therefore acrylic matt black enamel was sprayed on the bottom of the samples.

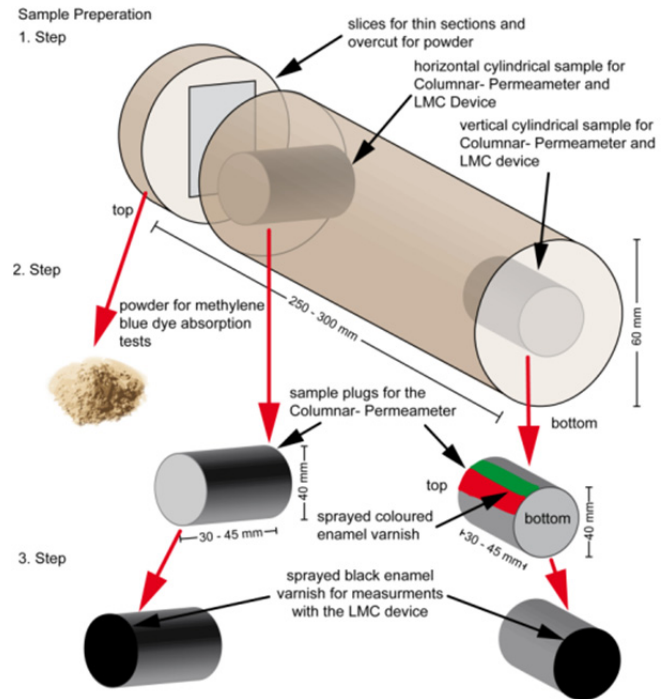


Fig. 10: Schematic sketch of the preliminary sample preparation.

Abb. 10: Probenaufbereitung für nachfolgende Messungen.

3 Permeability Measurements

The intrinsic permeability (k_i) was determined according to KLINKENBERG (1941) with a pressurized air driven, portable Columnar-Permeameter, which was invented by AIGNER & HORNING (2002). It is still under further development at the Institute of Applied Geosciences in Darmstadt and is described in detail by ARNDT & BÄR (2011). The pressurized air supply for the measurements can be covered by the local gas connection or by a standard diving cylinder, which gives the advantage to enable measurements in remote areas. Three different cylindrical adapters for the measuring cell with a diameter of 62, 40 and 25 mm are available. An automatic and manual measuring mode exists. The time required for a single measurement varies between 15 min for highly permeable samples and more than 60 min for slightly permeable samples. The specified measuring range is between 0.001 and 1000 mD.

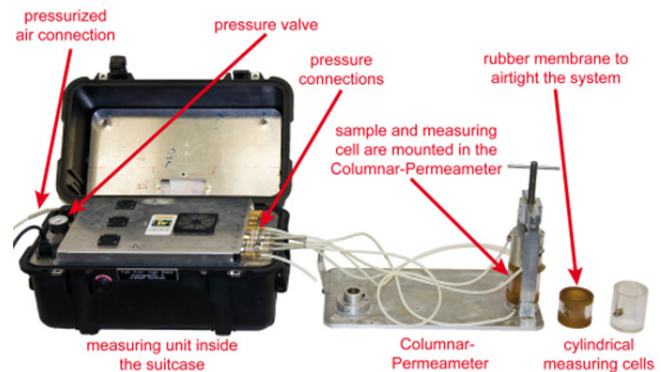


Fig. 11: Photo of the Columnar-Permeameter.

Abb. 11: Foto des Säulenpermeameters.

The gas permeability is measured at five different pressure stages (1050, 1250, 1500, 2000, 3000 and 5000 mbar) for each sample and is extrapolated to calculate the effective gas permeability for air under infinitely high air pressure. The pressure difference for all five stages remains identical and lies between 50 mbar for porous and up to a maximum of 1000 mbar for slightly porous samples. The apparent permeability k_a [m²] is calculated for every single measurement by the means of Darcy's law for compressible fluids and is plotted against the reciprocal mean pressure [$1/p^*$] in the corresponding pressure stage (Klinkenberg plot). The apparent permeability k_a is associated with the intrinsic permeability k_i by the means of the Klinkenberg-factor b . The approach is used for permeabilities $< 5 \cdot 10^{-14}$ m² and Klinkenberg-factors $> 0,24$ bar.

$$k_a = \frac{2 \cdot \eta \cdot h \cdot P_2 \cdot Q_2}{\pi \cdot r^2 \cdot (P_1^2 \cdot P_2^2)} \quad [8]$$

The reciprocal mean pressure [$1/p^*$] is calculated by equation [9]:

$$\frac{1}{P^*} = \frac{2}{(P_1 + P_2)} \quad [9]$$

4 Thermal Measurements

The portable Lambda Measuring Center (LMC) was used to determine thermal conductivity and thermal diffusivity. It is a contactless method for measuring solid materials based on the optical scanning method with a fixed point heat source (Popov et al. 1999). The heat source is a golden evaporated Osram lamp with maximum capacity of 150 W_e (Ruether 2011). The measuring range is between 0.5 W/(m·K) and approximately 5.0 W/(m·K). The samples must have a minimal length and width of 20 mm and a height of at least 10 mm (HAMM & THEUSNER 2010). The sensors measuring range lies between 4 °C and 38 °C with an error of approximately 1 %. The planar surface of the samples was sprayed black with acrylic matt black enamel to achieve identical initial conditions for each sample. To calculate the thermal conductivity of a sample it is necessary to use a standard of known thermal properties. It is possible to use one or two standards with different properties. Sample and standard are linked by equation [10] according to their respective thermal conductivities:

$$\lambda_{sample} = \lambda_{standard} \cdot \frac{\Delta T_{standard}}{\Delta T_{sample}} \cdot K \quad [10]$$

At the beginning of each measurement the LMC checks if the sample's temperature is stable. If steady state conditions are confirmed the unaffected temperature of the sample is detected as the initial temperature. Then the surface is heated up for 2 seconds with 15 % power of the 150 W_e Osram lamp (infrared emitter). The temperature of the sample will then decrease at a rate depending on its thermal conductivity. The temperature difference ΔT is measured at the third second of the analyzing process and the software determines the thermal conductivity by equation [10].

To calculate the thermal diffusivity a the sample is heated up again and the temperature is measured at a distance x to the heating point. The temperature maximum at a time t is determined by the software at the second measuring point. With t and x the thermal diffusivity can be calculated by equation [11] (HAMM & THEUSNER 2010):

$$t = \frac{x^2}{a \cdot 6} \quad [11]$$

The thermal diffusivity of the standard is well known and x is the same for both bodies (standard and sample). The thermal diffusivity of the sample can be calculated with an analogous relation to the thermal conductivity including the time t instead of ΔT :

$$a_{sample} = a_{standard} \cdot \frac{t_{standard}}{t_{sample}} \quad [12]$$

After HAMM & THEUSNER (2010) it is recommended to adjust the standard, heating power and heating period to the expected thermal conductivities and diffusivities of the sample. For the measurements a preset of 15 % heating power and a heating time of 2 seconds was chosen, because the thermal conductivity of the samples was expected to be around 1 W/(m·K).

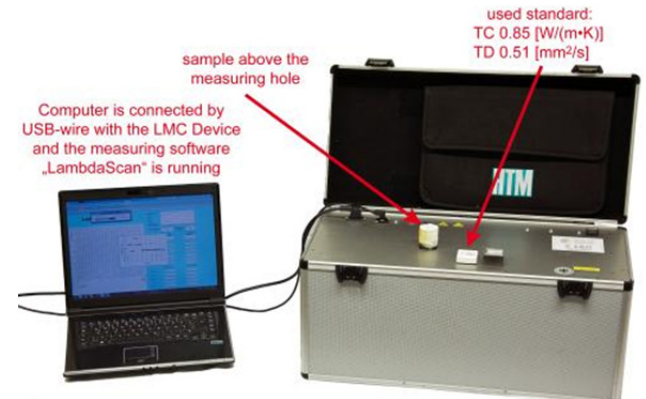


Fig. 12: Photo of the Lambda Measuring Center. The infrared emitter and temperature sensors are inside the box.

Abb. 12: Foto des LMC Messgerätes. Der Infrarotemitter und die Temperatursensoren befinden sich in dem Gehäuse.

5 Methylene blue dye adsorption tests

The methylene blue dye adsorption test is a semi-quantitative method to determine the amount of swelling clay (mainly smectite) in rocks and soil materials (GUNDERSON et al. 2000). The test is a common method for determining the swelling clay content in water based drilling fluids, but can also be used to estimate the smectite/smectite-illite clay content in hydrothermal systems. These clays represent the predominant rock alteration products in the 50 to 200 °C zone above the most high temperature, pH neutral, geothermal systems hosted by volcanics (BROWNE 1978). In such environments the clays form a cap that seals the reservoir to the top and to the sides, and thus helps to define the reservoir. The methylene blue (MeB) is an organic dye that shows a high selectivity for adsorption by reactive clay



minerals as smectite, but is unaffected for adsorption by common clay minerals. This allows a semi-quantitative estimation of the swelling clay content due to the amount of methylene blue dye adsorbed by the sample. This standardized (API 1988) technique uses a concentration of 3.74 g/l of methylene blue for the testing procedure. At this concentration the addition of 1 ml methylene blue dye solution is equivalent to an exchange capacity of 1 milliequivalent (1 meq) per 100 g cation. Based on the fact that smectites have an average cation exchange capacity of 100 meq/100g, 1 ml of methylene blue is equivalent to 1 % of swelling clay content. The method is called semi-quantitative because of the actual cation exchange capacity of the swelling clays, which may vary from 80 to 150 meq/100 g. This variation is caused by the structure of different types of clay in the smectite group. The lower detection limit for the methylene blue dye adsorption test is 1.5 ml MeB/g of clay, due to minor response to methylene blue dye by other clay minerals or other minerals with high cation exchange capacities as zeolites that could be present.

The cleaned and dried overcut material is pestled by a mortar. Then the powder is sieved through a 125 µm mesh. 1 g of the sieved powder is filled into an Erlenmeyer flask of 125 ml. Next 10 ml of distilled water is added and a pipette is used to add 1 ml of a 1 molar sulphuric acid (H₂SO₄). The Erlenmeyer flask is placed on a stir plate with a stirrer bar in it and heated up to boil. Afterwards the flask is removed from the stir plate. After a short cooling phase 1 ml of methylene blue dye with a concentration of 3.74 g/l is added from a burette. With a glass rod the suspensions is mixed up again and one drop of suspension is drawn using the glass rod. Then the glass rod is stamped on a filter paper. This procedure will be repeated until the end point is reached. This is the case if the cation exchange capacity is reached and a 1 to 2 mm wide pale blue dye halo is clearly visible around the dark blue stamp. After the first halo appears the Erlenmeyer flask is placed back on the stir plate and briefly heated up again. However, no more methylene blue is added now. After two minutes another stamp has to be done on the filter paper with the glass rod. If the initial halo is confirmed by the two minute repeat test, the end point has been reached. If no halo appears in the repeat test another 1 ml of the dye must be added and the Erlenmeyer flask must be briefly heated up again and stirred. Another stamp is also necessary. Usually the end point is reached now, but a repeat test should be done to confirm the result.

6 Measurement Results

The measured results of permeability, thermal conductivity, thermal diffusivity and methylene blue dye adsorption tests are summarized in the stratigraphic logs of figure 14 for the wells THM18, TH18 and THM19. The results are characterized by a great variability depending on the source rocks (educts), the rank and intensity of the hydrothermal alteration, depth, primary permeability etc.

6.1 Permeability

The permeability is highly variable (0.01 – 1000 mD) but generally decreases with depth, while the thermal conductivity increases with depth. The rhyolitic breccia of TH18

shows the highest mean values of up to 360 mD. The pumice-rich crystal tuffs of the Middle Huka Fall Formation (MHF) and Waiora Formation (WAF) are characterized by relatively constant values of around 10 mD.

Lithologies of greater permeabilities such as the pumice-rich crystal tuffs are more affected by hydrothermal alteration (see figure 13) and therefore show significant changes of their properties. With an increase of the fine fraction the permeability decreases. Especially the sedimentary derived lithologies of the Upper Huka Fall Formation (UHF), MHF and WAF show greater variations in permeability. Impervious, clay-rich layers determine the total permeability of these formations.

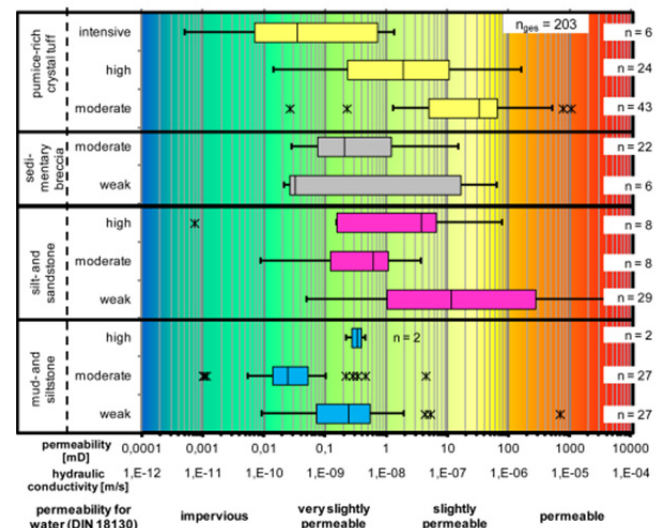


Fig. 13: The diagram shows the influence of hydrothermal alteration on permeability exemplarily for different lithologies.

Abb. 13: Das Diagramm zeigt den Einfluss der hydrothermalen Alteration auf die Permeabilität exemplarisch für einige Einheiten.

Increasing hydrothermal alteration intensity within the Spa Andesite formation (Spa), consisting of andesitic lava flows and hydrothermal breccias causes increased permeability and decreased thermal conductivity. This could be an effect of the intensive fracturing within the andesite, whereas number and width of the fractures increase towards the edge of the andesite lava flow. The centre of the lava flow consists of relatively homogeneous andesite lava, while the boundaries consist of a hydrothermal andesite breccia, which is characterized by higher alteration intensities.

6.2 Thermal Conductivity

The thermal conductivity of the samples generally increases with depth. The thermal conductivity varies between 0.35 and 2.50 W/(m·K) showing a negative correlation with the permeability. Figure 15 shows the effect of hydrothermal alteration on the thermal conductivity. Mud- and siltstones are characterized by a small range of measured values between 0.5 and 1.4 W/(m·K). Silt- and sandstones show increased thermal conductivities with increasing alteration intensities. Pumice-rich crystal tuffs also have very high thermal conductivities when intensively altered. The compact andesitic and rhyolitic lava units and the igneous breccia show the highest thermal conductivities with average

mean values of more than 1 W/(m·K) and maxima greater than 2.0 W/(m·K). Other lithologies are usually characterized by low thermal conductivities between 0.5 and 1.5 W/(m·K). As might be expected, with increasing rock strength the thermal conductivity also increases.

6.3 Methylene Blue Dye Adsorption Tests

A decreased amount of swelling clay (smectite) indicates a higher alteration rank. Peak concentrations occur at the

Upper (UHF) and Lower Huka Fall Formation (LHF). A high amount of clay in highly altered sedimentary lithologies leads to low permeabilities, typically for caprocks. Smaller maxima occur within the WAF, indicating a general decrease of smectite with depth due to its natural stability range (70 – 160 °C). A high amount of swelling clay generally correlates with low thermal conductivities.

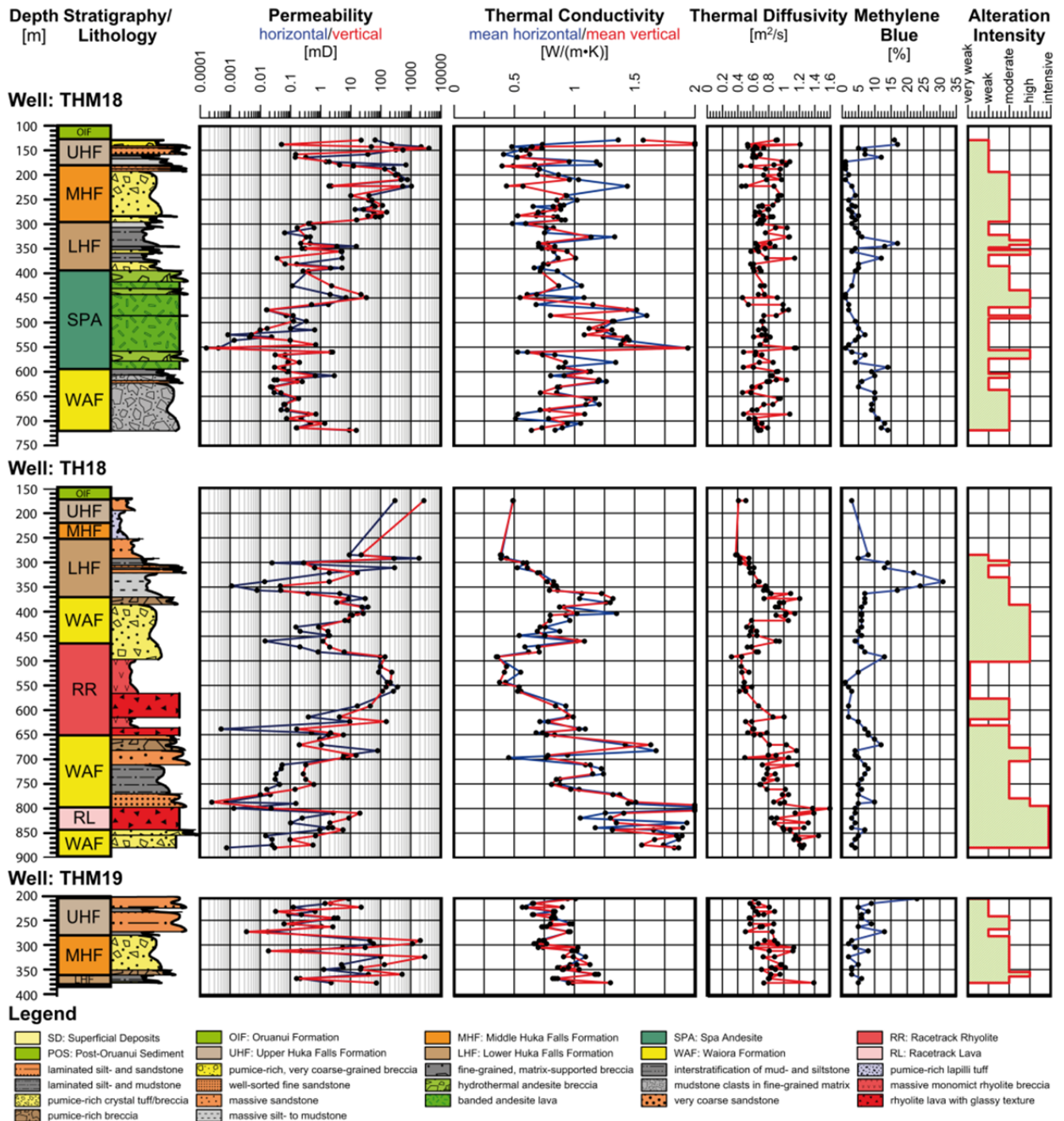


Fig. 14: Stratigraphic logs show the measurement results of the wells THM18, TH18 and THM19.

Abb. 14: Stratigraphische logs zeigen die ermittelten Messwerte der Bohrungen THM18, TH18 und THM19.

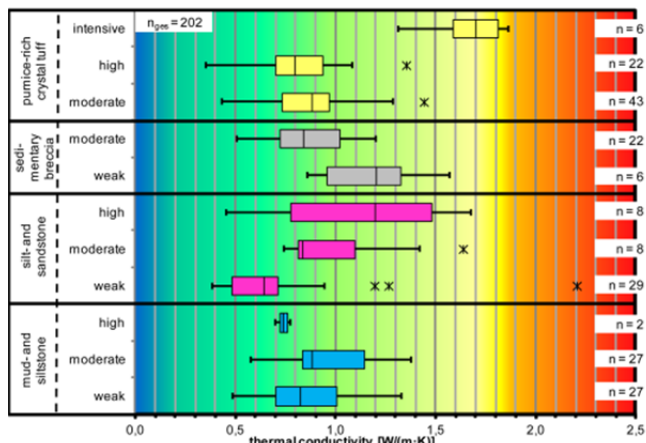


Fig. 15: The diagram shows the influence of hydrothermal alteration on thermal conductivity for different lithologies (next page).

Abb. 15: Das Diagramm zeigt exemplarisch den Einfluss der hydrothermalen Alteration auf die Wärmeleitfähigkeit (nächste Seite).

6.4 Results of thin section analyses

With increasing depth the temperature, intensity and rank of the hydrothermal alteration also increases. The alteration type changes from argillic in the shallower parts to propylitic at greater depths (below 600 m). The primary mineral assemblage is predominantly replaced by clay minerals, calcite and secondary quartz (see figure 16). Therefore, hydrothermal alteration is generally prograde.

WAF: 439.97 m; TH18 (crossed nicols) WAF: 642.50 m; TH18 (crossed nicols)

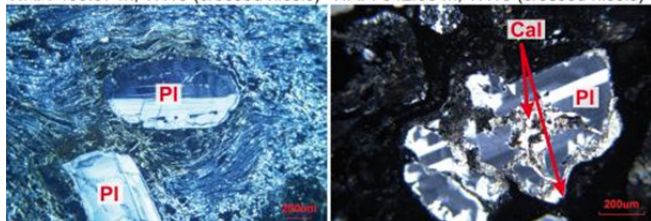


Fig. 16: The photomicrographs show a fresh plagioclase (left) and partially replaced plagioclase (right) in vitric pumice-rich tuffs.

Abb. 16: Die Dünnschliffbilder zeigen einen unalterierten (li.) und einen teilweise ersetzen Plagioklas (re.) in vitrischen Bimstufen.

However, the hydrothermal alteration also depends on the mineralogy of the host rocks (Bowen's reaction series), the texture, the primary permeability (e.g. veins and amygdaloids), the chemistry of the fluids etc. (compare to figure 17). Argillic alteration affects the shallower formations and typically forms smectite, illite and smectite-illite mixed-layer clays with alteration intensities from weak to high.

Intensively altered rocks occur only in the deeper parts of the system, influenced by the propylitic alteration including silicification processes. The result of silicification is the precipitation of secondary silica. Greater permeabilities, such as fractures seem to facilitate this process. The thermal conductivity increases consequently by an increasing amount of quartz.

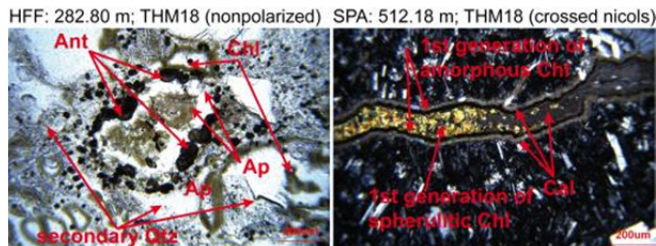


Fig. 17: The photomicrographs show different alteration textures.

Abb. 17: Verschiedene Alterationserscheinungen in Dünnschliffen.

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