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From Faults to Flow: How Fracturing and Hydrothermal Alteration Shape Geothermal Reservoirs in Crystalline Rocks

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ABSTRACT

This study explores the impact of fracturing and hydrothermal alteration on porosity, permeability, and fluid flow in crystalline basement rocks formed within fault zones at the Kivetty site, Central Finland. These processes are key to developing geothermal reservoirs in areas typically characterized by low-permeability crystalline cratons, particularly in non-volcanic, stable continental regions. We analyzed 130 granitic and granodioritic samples from six deep boreholes using petrophysical measurements at room conditions (e.g. density, elastic wave velocity, thermal conductivity, porosity), and gas-based permeability tests under confining pressure. Additionally, we conducted a detailed mineral and pore characterization on a sub-set of samples using X-ray computed tomography (XCT), micro-XRF analysis (μXRF), and semi-automated mineral mapping using the Advanced Mineral Identification and Characterization System (AMICS). Complementary, we contrast our laboratory results with in-situ legacy data from long-term cross-well hydraulic pumping tests with the aim to assess reservoir-scale hydraulic connectivity in the study area.

Results show that hydrothermally altered and fractured rocks formed within the core and damage zones of faults exhibit significantly higher porosity (up to 20%), permeability (k = 10^{-12} m^2), and pore connectivity (up to 94%) compared to unaltered host rocks (porosity ~1%, k <10^{-16} m^2, connectivity ~54%). These reservoir parameter enhancements are primarily linked to mineral dissolution (mainly biotite, albite, K-feldspar, and quartz), which is commonly linked to formation of secondary minerals such as chlorite, muscovite, and Fe oxides.

The permeability of these altered rocks remains high up to a confining pressure of 50 MPa (simulating overburden depth of nearly 2 km). This phenomenon is also observed in in-situ drawdown responses test from the boreholes, where large-scale hydraulic transmissivity of 1.20 × 10^{-4} m^2 s^{-1} is recorded at depths of up to 1.5 km from the pumped zone.

Our study demonstrates that fluid flow data obtained from laboratory tests on small 2 × 4 cm rock cylinders are consistent with results from in-situ pumping tests (k = ~10^{-12} m^2). In detail, our findings show that fault-related alteration significantly enhances the porosity, permeability, and large-scale hydraulic properties of crystalline rocks while also reducing other petrophysical parameters such as density, elastic wave velocity, electrical resistivity, and thermal conductivity, key for heat and fluid flow in basement crystalline areas. Altered fault zones act both as natural flow pathways and reservoirs, sustaining lateral fluid circulation at depth, and confirming their potential for geothermal energy extraction. This study highlights the importance of integrating structural, petrophysical, and mineralogical characterization into a unified model to assess the potential of deep geothermal targets in stable crystalline cratons.

1. INTRODUCTION

Fault zones in crystalline bedrock play a fundamental role in controlling deep groundwater flow and heat transport in typically low-permeability crystalline terrains (Diamond et al., 2018). In regions like Finland, which lack high-temperature geothermal gradients or young volcanic systems, fractured crystalline rocks are a promising target for developing unconventional geothermal resources. The hydraulic behavior of these systems is often considered to be governed primarily by fracture network, connectivity, and mineralogy within fault zones, with limited contribution from the rock matrix under most conditions.

Faults and fractures are well known to form the main flow pathways in many geothermal systems globally (e.g., Jolie et al., 2015). Less commonly considered, however, is that mineral alteration can also play a significant role in crystalline geothermal reservoirs—particularly in prospects within the Upper Rhine

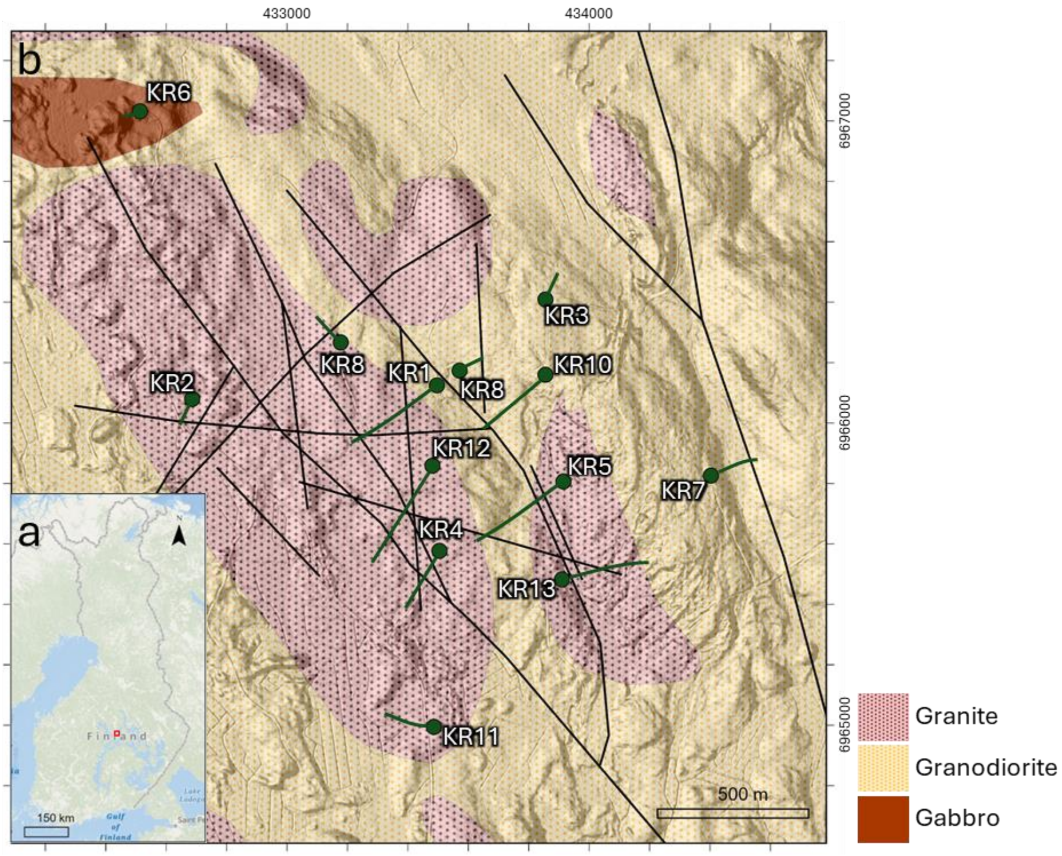

Figure 1: Geological map of the Kivetty study area with borehole locations. Green dots mark borehole collars, and green lines indicate borehole orientations. Black lines represent interpreted fault zones. The background shows a hillshade from LiDAR data, overlaid with bedrock units. Inset (a) shows the regional location in Central Finland.

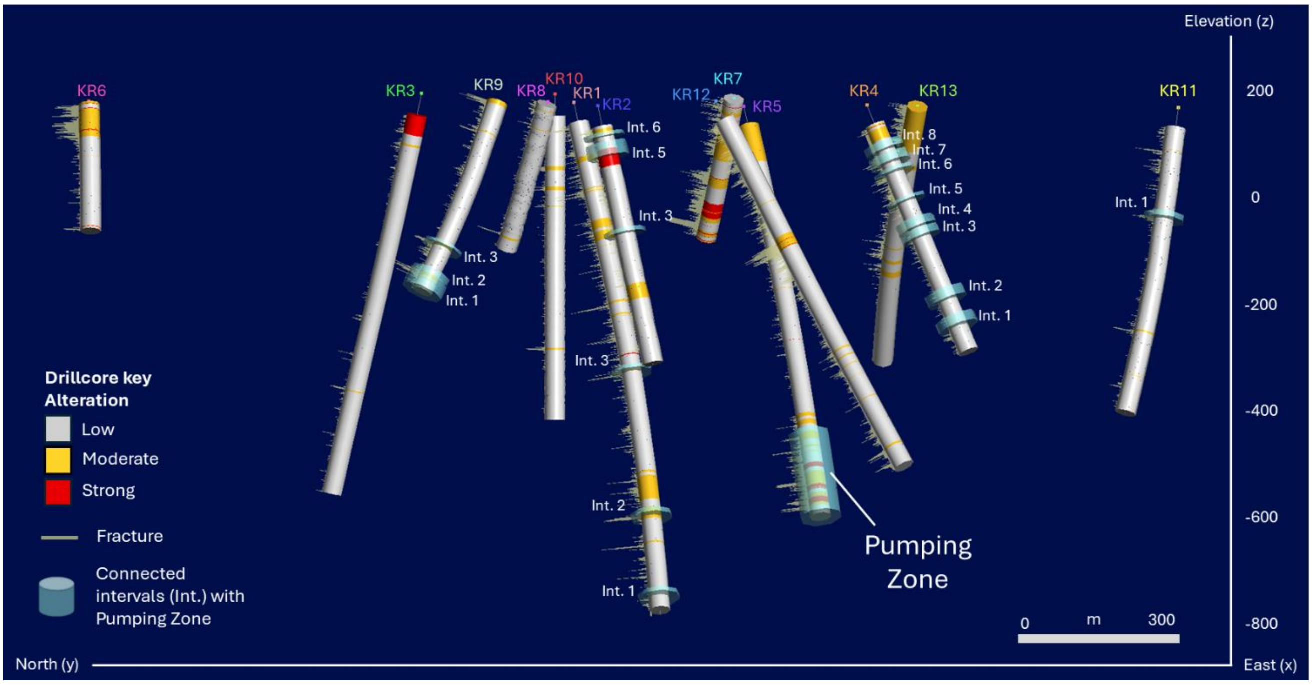

Figure 2: Three-dimensional visualization of boreholes at the Kivetty site, highlighting the spatial extent of alteration, fracturing, and hydraulic connectivity in relation to the KR5 pumping interval. Boreholes are color-coded by alteration intensity, and fractures are shown as thin lines. Blue cylinders indicate observation intervals hydraulically connected to the KR5 pumping zone (681.3–852.3 m depth).

Graben in Western Europe, where porous and permeable crystalline rocks make up the primary reservoir units (Vidal & Genter, 2018). Previous studies across Fennoscandia have shown that hydrothermal alteration and mechanical damage zones around fractures can significantly enhance fluid flow by increasing porosity and permeability (Bischoff et al., 2024). These altered rocks act as preferential pathways for deep water circulation, influencing thermal regimes and the feasibility of geothermal exploitation in continental shield settings.

The Kivetty site in Central Finland provides an exceptional setting for investigating fluid flow in crystalline rock. It contains a legacy dataset of deep boreholes, structural logs, and hydrogeological tests—making it ideal for assessing how fault-controlled fracturing and hydrothermal alteration influence permeability and hydraulic connectivity. This study integrates long-term pumping test data from borehole KR5 with petrophysical and mineralogical analyses to investigate how fault-controlled alteration zones enhance the permeability and hydraulic connectivity of these rocks—key factors controlling heat and fluid flow in geothermal reservoirs. Our findings contribute to the understanding of how permeability is generated and sustained in stable, low-permeability cratonic environments.

2. KIVETTY SITE

The Kivetty site is located in Äänekoski in Central Finland, within the Central Finland Granitoid Complex (CFGC). The region consist of ~1.88 Ga Paleoproterozoic crystalline rocks formed during the Svecofennian Orogeny, including granitoids, and migmatites (Heilimo et al., 2018). The CFGC is dominated by plutonic lithologies, ranging from diorites to granodiorites and granites (Mikkola et al., 2018; Figure 1).

Between 1987 and 2000, Kivetty was extensively investigated as part of Finland's national program for the deep geological disposal of spent nuclear fuel (Anttila et al., 1999). A total of 13 deep core boreholes (KR1–KR13) were drilled, reaching depths of up to ~1000 m (Figure 1 and 2). The bedrock at the Kivetty site consists predominantly of porphyritic granodiorite, with intrusions of younger granite and minor gabbroic bodies interpreted to be older than the granodiorite. Structural analyses reveal a complex system of steeply dipping faults and fractures with varied orientations. These zones are significantly more hydraulically conductive than the surrounding intact rock, as identified through detailed core logging, surface mapping, and borehole geophysical surveys.

Core observations also indicate the presence of brittle deformation zones associated with alteration halos, particularly around fractures and faults (Saksa et al., 1998). These altered zones are interpreted as products of past hydrothermal fluid circulation, which has transformed primary minerals and created interconnected pore networks that locally enhance porosity and permeability within the crystalline bedrock.

To evaluate how fault-related alteration and fracturing influence deep fluid flow at the Kivetty site, we combined hydraulic testing with detailed mineralogical and petrophysical analyses. The following sections describe the long-term pumping test conducted in borehole KR5, along with laboratory analyses performed on selected core samples.

3. MATERIAL AND METHODS

3.1 Hydraulic Testing and Borehole Monitoring

A long-term pumping test was conducted in borehole KR5 at an interval from 681.3 to 852.3 m to investigate hydraulic connectivity within the fractured crystalline bedrock (Figure 2; Hänninen, 1997). The test lasted 27 days, with an average discharge of 18.9 L min^{-1} and a total volume of 736,000 L extracted. In addition to the long-term pumping test, a series of 2 m interval packer tests were performed in KR5 to obtain high-resolution permeability data.

Hydraulic head variations were monitored in multiple nearby boreholes (KR1, KR2, KR4, KR9, KR11; see Figure 1 for locations) using pressure transducers and manual water-level measurements. Drawdown responses were interpreted using Theis analytical solutions, and transmissivity values were estimated for connected intervals. These values were used to assess hydraulic connectivity and permeability distribution.

3.2 Core Sampling and Classification

A total of 130 core samples were selected from six deep boreholes at the Kivetty site (KR1, KR3, KR4, KR5, KR12, and KR13) to investigate the petrophysical and structural controls on permeability and fluid flow. Based on core logging observations, samples were grouped into four main textural categories: (i) massive, (ii) fractured, (iii) brecciated, and (iv) altered rocks.

3.3 Petrophysics Analyses

Petrophysical tests were conducted on cylindrical rock samples (2 cm × 4 cm and 4 cm × 8 cm). Density, porosity, P-wave velocity, electrical resistivity, and thermal conductivity were measured at the Geological Survey of Finland (GTK) laboratories, while connected porosity and permeability were both measured using gas at the Strasbourg Institute of Earth & Environment, University of Strasbourg (France).

Dry bulk density and connected porosity were determined using the Archimedean triple-weight method. Samples were oven-dried at 105 °C and subsequently saturated by submerging them in water at room temperature for several days. A subset of porous samples was further tested using a gas pycnometer with helium as the working gas. P-Wave Velocity was measured on water-saturated samples using a 1 MHz transducer system developed at GTK, with a precision of ±10 m/s. Thermal conductivity was measured under saturated conditions using a Hot Disk TPS 2200 instrument equipped with a 5501 Kapton sensor (radius 6.403 mm), based on the transient plane source (TPS) method. Electrical resistivity was measured galvanically on fully saturated samples using a Sample Core Induced Polarization (SCIP) tester (Instrumentation GDD) with a two-electrode configuration. Measurements were performed at room temperature under time-domain conditions, with current injection and voltage measurements conducted through the same electrodes.

Permeability was measured on 27 samples at room temperature and a confining pressure of 1 MPa using a steady-state gas permeameter and nitrogen gas. To simulate subsurface confining pressure conditions, one representative sample was selected and tested under confining pressures up to 50 MPa using a triaxial pressure vessel and argon gas. In both cases, permeability was calculated using Darcy's law, with Klinkenberg and Forchheimer corrections applied if and when necessary.

In addition, high-resolution X-ray computed tomography (XCT) was performed at GTK using a GE Phoenix v|tome|x s system equipped with a 240 kV microfocus tube, operated at 150 kV and 75 µA with a 0.1 mm Cu beam filter. Each sample was scanned in four overlapping segments (2700 projections per segment, 500 ms exposure time), which were combined into a single 3D volume with a spatial resolution of 11.0 µm—sufficient to resolve dominant porosity features. Reconstruction was done using GE datos|x 2 with a beam hardening correction of 4. Porosity quantification and visualization were carried out using two-phase watershed segmentation in ThermoFisher PerGeos 2020.2.

3.4 Mineralogical Characterization

Elemental µ-XRF mapping was performed using a Bruker Micro-XRF M4 Tornado Plus, equipped with a 30 W Rh X-ray tube and dual 30 mm² silicon drift detectors (SDDs), operated under a 2 mbar vacuum. Maps were acquired with a 20 µm step size and 20 ms dwell time to identify elements (e.g., Fe, K, Ca, S) associated with hydrothermal alteration and fracture fillings.

Automated Mineralogy (AMICS): Mineral mapping was carried out using the AMICS software package integrated with the Bruker Micro-XRF M4 Tornado Plus. Minerals were classified by matching XRF spectra to a reference library using χ^2 fingerprinting. Image segmentation and clustering algorithms were subsequently applied to refine mineral boundaries and resolve unclassified or complex mineral mixtures.

4. RESULTS

4.1 Borehole KR5 and Petrophysical Signatures

Borehole KR5 provides a detailed vertical profile through the crystalline basement at Kivetty site, intersecting mainly granodioritic bedrock (Figure 3). Above a depth of 680 m, the rock is relatively intact, with low fracture frequency, limited hydrothermal alteration, and consistent petrophysical trends. Parameters such as P-wave velocity, density, and electrical resistivity show minimal variations in this upper section. In contrast, between 680 and 830 m, the core intersects a strongly fractured and hydrothermally altered interval, interpreted as a multicore fault zone composed of fractured, brecciated, and altered rocks (Figure 3; Mitchell & Faulkner, 2009).

Drill core observations and wireline logs show that this altered interval is marked by increased fracture frequency and reduced rock quality designation (RQD), as well as systematic decreases in P-wave velocity, density, and electrical resistivity. On the other hand, permeability values, measured at 2-meter intervals, increase by several orders of magnitude within the fault zone (up to $k = 10^{-12}$ m^2), while values outside the zone remain low ($k = 10^{-18}$–10^{-16} m^2).

Petrophysical trends observed in the KR5 borehole are consistent with core samples measured in the laboratory from multiple boreholes across the Kivetty site. As shown in the crossplots (Figure 4), increasing porosity correlates with decreasing density, P-wave velocity, and thermal conductivity, and with increasing permeability (up to 2.5×10^{-13} m^2). Altered and brecciated samples consistently fall within the high-porosity, high-permeability domain (Figure 4).

Overall, borehole KR5 provides a clear example of a deep, permeable fault zone. The integration of lithological, structural, and petrophysical evidence supports its interpretation as a major fluid pathway and sets the stage for the hydraulic connectivity analysis discussed in the following sections.

4.2 Pumping Test and Hydraulic Connectivity

Hydraulic responses to the KR5 pumping test were observed in several nearby boreholes (Figure 2), with variable drawdown amplitudes depending on the structural connection and distance from the pumped interval. Figure 5 shows the time series of hydraulic head changes in four selected observation intervals: KR1 Interval 4, KR2 Interval 5, KR4 Interval 5, and KR9 Interval 3. Each curve displays a distinct decline in hydraulic head following the onset of pumping. The largest drawdown (~2.0 m) was recorded in KR1 Interval 4, while the smallest (~0.2 m) was observed in KR2 Interval 5.

Transmissivity values for the monitored intervals, estimated using Theis curve fitting, are presented in Table 1. The highest transmissivity (1.20×10^{-4} m^2 s^{-1}) was recorded in borehole KR4 Interval 5 (depth 135–194 m), located approximately 1.5 km from the pumped zone in KR5. A similarly elevated transmissivity was observed in KR9 Interval 3 (depth 302–309 m), situated 850 m from the pumping site and intersecting a major fracture. In contrast, KR2 Interval 5 (depth 73–100 m, 1 km from KR5) exhibited lower transmissivity (2.20×10^{-6} m^2 s^{-1}), likely indicating more limited or indirect connectivity to the pumped fracture zone. Estimated

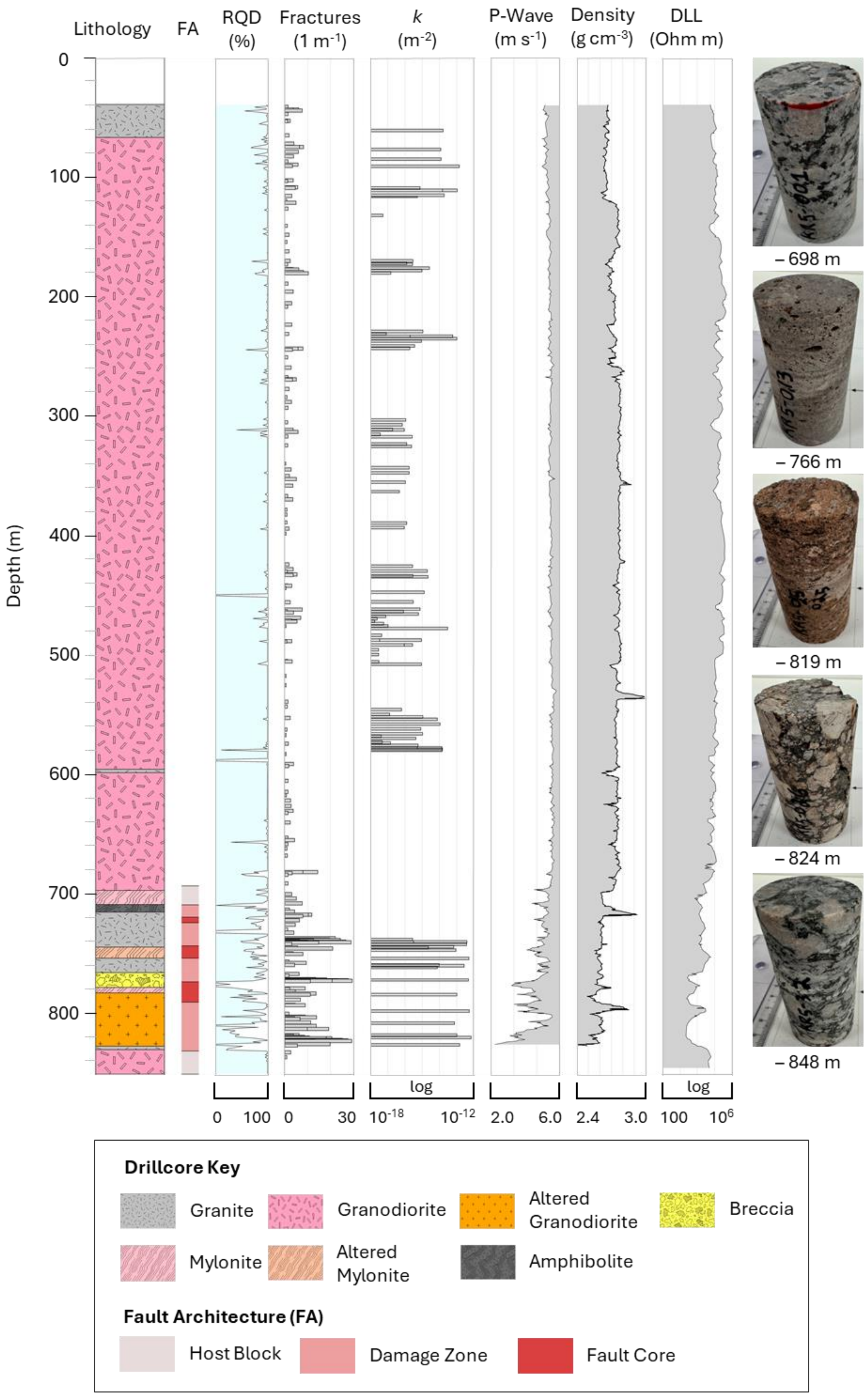

Figure 3: Geological and geophysical borehole log of KR5, Kivetty site. Rock types are color-coded, with granodiorite dominating the upper section. The log presents lithology, fracture frequency, and petrophysical properties alongside core images, and highlights a major fault zone (FA) associated with increased fracturing and permeability, as well as a decrease in P-wave velocity, density, and electrical resistivity (DLL)

permeability values, derived from transmissivity and interval thickness, range from ~10^{-14} to 10^{-12} m^2 (Table 1).

The radial extent of measurable drawdown (475–1500 m, Table 1) indicates that the fault zone intersected in KR5 is part of a hydraulically connected pore network that affects the pressure within these faults over km-scale lateral and vertical distances.

4.3 Mineralogical Changes and Pore Connectivity

The hydraulic responses and permeability trends observed across the boreholes are further supported by high-resolution imaging of mineralogical alteration and pore architecture. While pumping tests define the large-scale connectivity between boreholes, μ-XRF, AMICS, and XCT analyses help explain the microscale processes responsible for enhanced reservoir properties.

Figure 6 presents a visual comparison of granitic samples at different stages of hydrothermal alteration, from low to strong intensity. μ-XRF elemental maps reveal significant mobility of elements such as Na, K, Ca, Fe, and Ti. These elements are found where strong alteration is observed. Additionally, AMICS mineralogical maps show a progressive replacement of primary minerals, including albite, K-feldspar, biotite, and quartz, by secondary alteration products such as chlorite, muscovite, iron oxides, and clay minerals. This replacement is often associated with mineral dissolution, which creates new voids and enhances intergranular porosity. Porosity maps show increasing pore space and fracture density in strongly altered samples.

Complementary XCT data (Figure 7) provide 2D and 3D views of these pore networks. With increasing alteration intensity, the samples show a marked increase in total porosity (from ~2% to 30%), pore connectivity (from 20% to 94%), and permeability (from 1.5×10^{-16} m^2 to 2.5×10^{-13} m^2). The transition from isolated microvoids to a fully interconnected pore system explains the substantial enhancement of fluid mobility in altered crystalline rock.

5. DISCUSSION

5.1 Permeability Enhancement through Fracturing and Hydrothermal Alteration

The integrated dataset from the Kivetty site demonstrates that fault-related deformation and hydrothermal alteration are the primary controls on permeability enhancement in the crystalline basement. The transition from massive, unaltered granodiorite to a brecciated and altered fault core in borehole KR5 is accompanied by a systematic and well-defined increase in porosity and permeability.

Mineralogical and geochemical analyses reveal a secondary mineral paragenesis characterized by the replacement of biotite with chlorite, K-feldspar with muscovite, and the presence of iron oxides and clay minerals (Reijonen et al., 2024). This assemblage is consistent with phyllic–propylitic alteration, typically associated with temperatures ranging from ~200–300 °C and low-pH fluids, which promote mineral dissolution and the formation of secondary mineral phases (Giggenbach, 1984). In some cases, primary minerals have been completely dissolved, leaving behind voids that now serve as connected pore space. These conditions are indicative of moderate- to high-temperature fluid–rock interaction and suggest that the KR5 fault zone experienced sustained hydrothermal activity during its history.

Similar alteration assemblages have been extensively documented in other geothermal systems (e.g., the Upper Rhine Graben, French Massif Central, or Taupo Volcanic Zone; Wyering et al., 2014; Duwiquet et al., 2019; Glaas et al., 2021), where fluid circulation along fault zones drives large-scale mineral alteration. However, in low-enthalpy crystalline settings such as Fennoscandia, the extent and preservation of such alteration is rarely reported (e.g., Bischoff et al., 2024), which makes the Kivetty site a valuable case study. The presence of these mineral phases supports the interpretation that permeability enhancement in KR5 is not solely due to mechanical fracturing but is also closely tied to chemical alteration that promotes long-term porosity and connectivity.

Experimental evidence further supports this interpretation. Laboratory studies have shown that feldspar and biotite dissolution under low-pH conditions (pH ~4) can significantly increase permeability in fractured granite (Takahashi et al., 2023). These conditions are consistent with the inferred geochemical evolution at Kivetty, where both high-temperature alteration and later-stage, lower-temperature weathering have contributed to the development and preservation of permeable zones.

5.2 Multi-Scale Connectivity and Reservoir-Scale Implications

The hydraulic behavior observed at Kivetty provides clear evidence that permeability in the crystalline basement rocks is not randomly distributed but is instead structurally organized along fault zones. The spatial extent of pressure propagation, reaching boreholes over 1.5 km away, indicates that these altered zones form laterally extensive and hydraulically continuous networks capable of sustaining flow rates on the order of tens of liters per second, suitable for commercial geothermal applications.

The observed large-scale hydraulic connectivity indicates that fault zones can act as the functional boundaries of geothermal reservoirs in crystalline rocks. Instead of being isolated features, these zones likely link separate fracture clusters into a continuous flow system. This has important implications for geothermal development: targeting altered fault zones may reduce or even eliminate the need for additional soft stimulation techniques, especially in low-enthalpy settings.

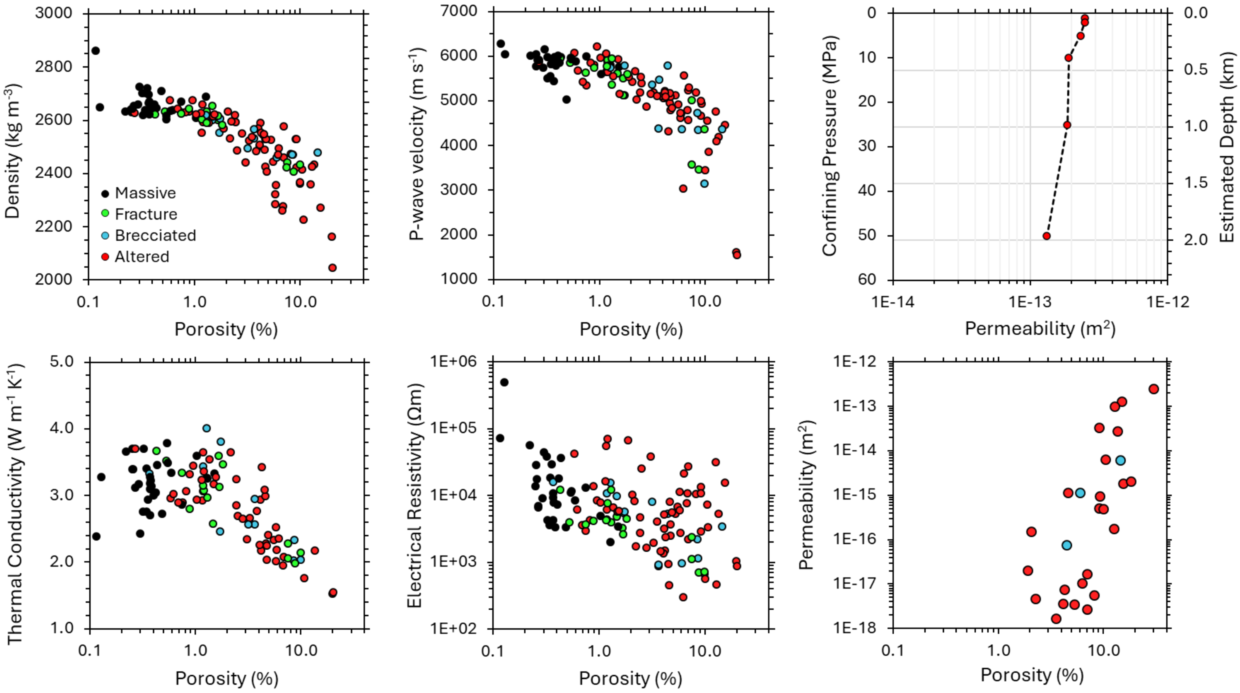

Figure 4: Relationships between connected porosity and selected physical properties of rock samples categorized as massive (black), fractured (green), brecciated (blue), and altered (red). Density, P-wave velocity, thermal conductivity, and electrical resistivity (galvanic) generally decrease with increasing porosity, while permeability increases. Permeability values of one altered sample was measured under confining pressures up to 50 MPa.

Table 1: Transmissivity and estimated permeability for selected observation intervals during the KR5 pumping test at Kivetty. Transmissivity values are based on Theis analysis, and permeability was calculated using the corresponding packer-isolated interval thickness. Distances represent the radial distance from the pumped borehole KR5 to each interval in different boreholes.

Borehole	Packer Interval	Depth Interval (m)	Thickness (m)	Distance (m) from Pumping Test	Transmissivity [m^2 s^{-1}]	Permeability [m^2]
KR1	4	533–540	5.7	475	4.30×10^{-5}	7.70×10^{-13}
KR9	3	302–309	7	850	1.40×10^{-5}	2.00×10^{-12}
KR2	5	73–100	9.3	1000	2.20×10^{-6}	2.40×10^{-14}
KR4	5	135–194	10.7	1500	1.20×10^{-4}	1.15×10^{-12}

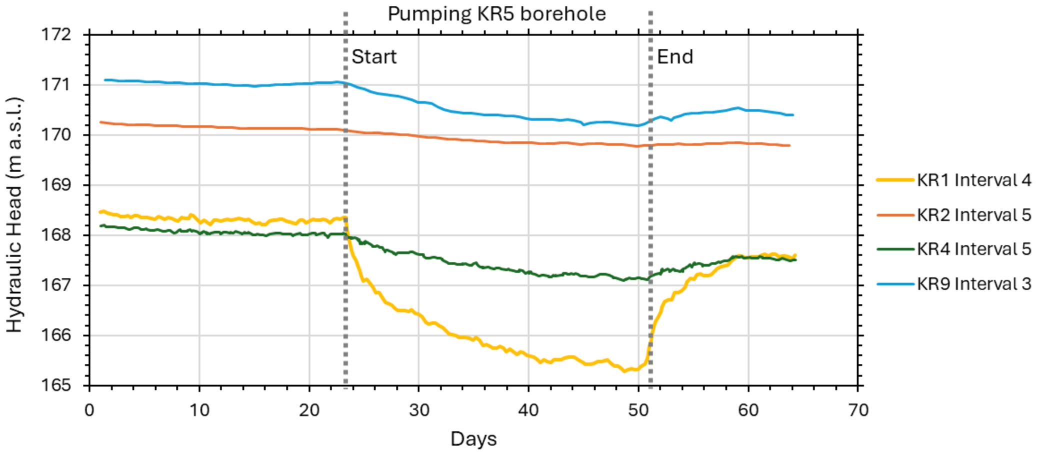

Figure 5: Time series of hydraulic head in selected observation boreholes during the KR5 pumping test at Kivetty. The vertical dashed lines indicate the start and end of pumping (7 January – 3 February 1997). Each curve represents a different borehole interval, with variable drawdown responses reflecting differences in hydraulic connectivity and fracture zone intersections.

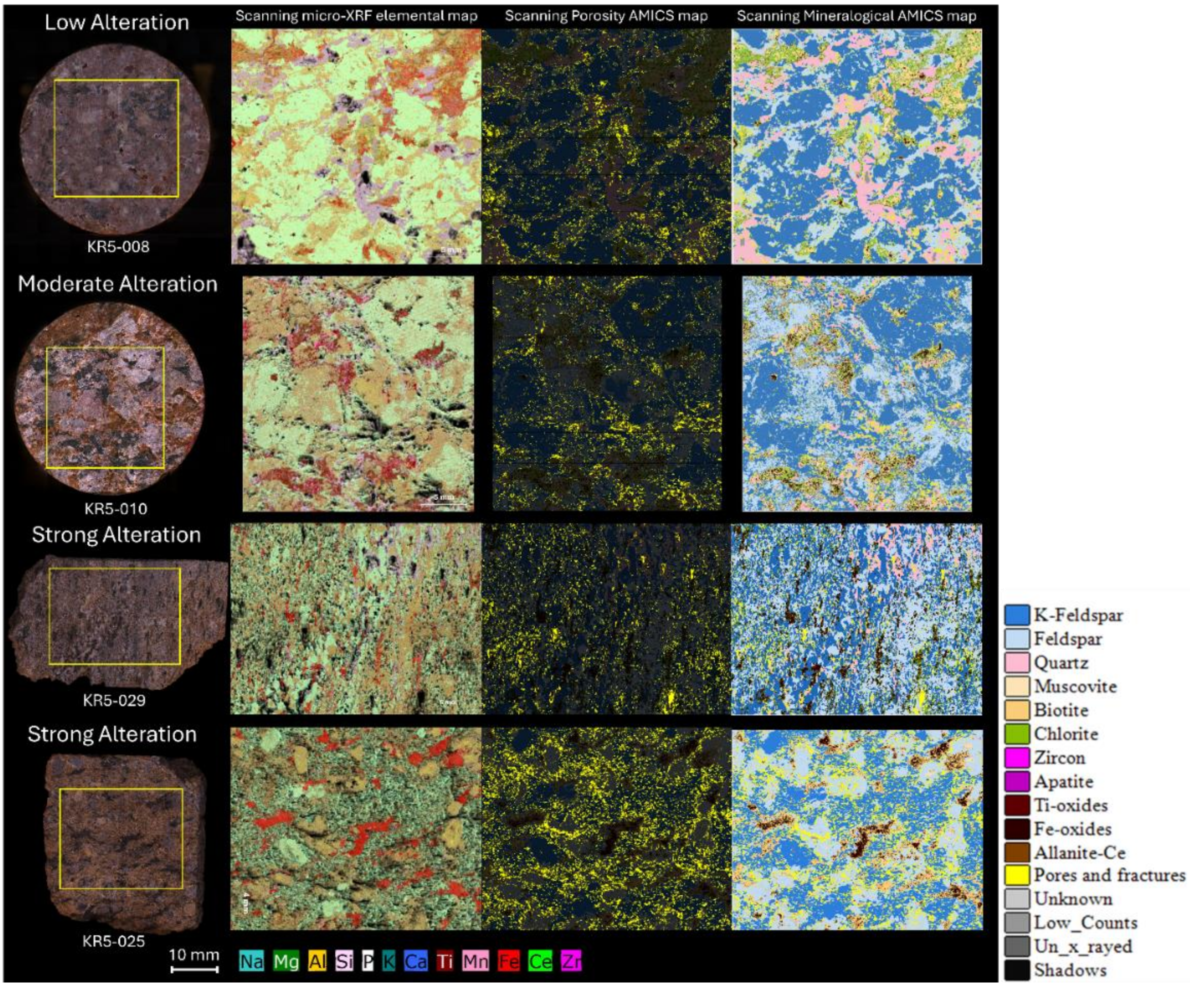

Figure 6: Visual comparison of granite samples at different stages of hydrothermal alteration (Low to Intense) using multiple analytical methods. Columns from left to right show: (1) optical image of the sample surface; (2) elemental distribution map from scanning micro-XRF, highlighting major elements (Na, Mg, Al, Si, P, K, Ca, Ti, Mn, Fe, Ce, Zr); (3) porosity map from AMICS analysis, with yellow representing pore space and fractures; and (4) mineralogical map from AMICS scanning, showing distribution of key minerals including K-feldspar, feldspar, quartz, muscovite, biotite, chlorite, and iron oxides. Scale bar: 10 mm.

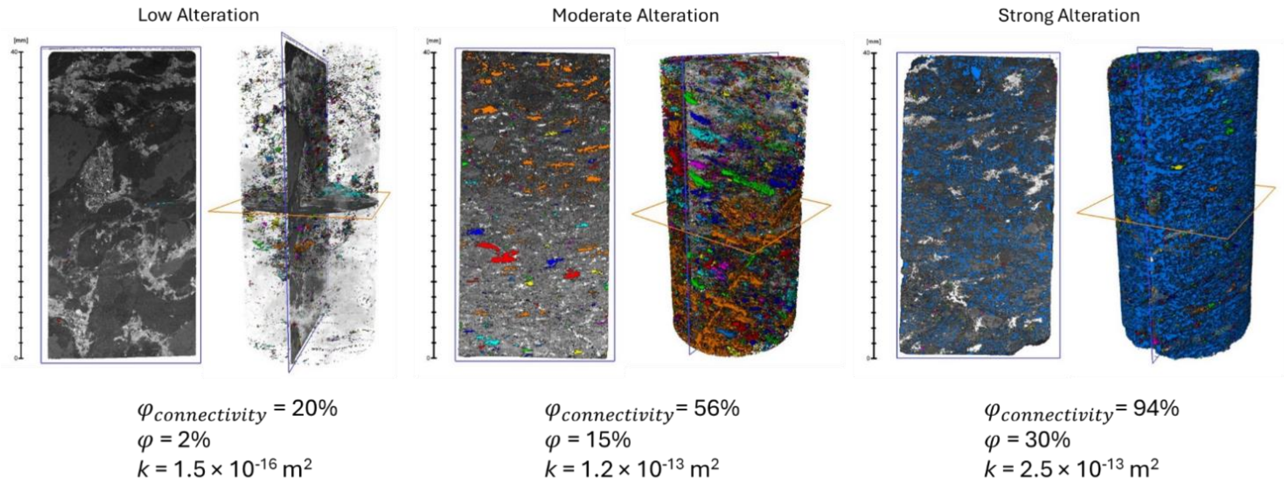

Figure 7: X-ray computed tomography (XCT) visualizations of granite samples under increasing hydrothermal alteration intensity (Low, Moderate, Strong). Each sample shows 2D cross-sections and 3D renderings of segmented pore networks. Quantitative values for porosity (φ), pore connectivity ($\varphi_{connectivity}$), and permeability (k) show the progressive enhancement of fluid pathways with alteration intensity, highlighting the relationship between mineralogical transformation and transport properties.

This degree of long-range connectivity is consistent with numerical models, showing that mineral dissolution during water–rock interaction in granite can sustain, or even enhance porosity over geothermal operational timescales (Alt-Epping et al., 2013). Additionally, the structural and mineralogical features observed at Kivetty are similar to those reported at the United Downs Deep Geothermal Project in Cornwall, UK, and in the French Massif Central, where fault-hosted permeability has enabled deep fluid circulation in otherwise low-permeability granite (Duwiquet et al., 2019; Reinecker et al., 2021). These examples illustrate that, when fault zones are permeable, they can maintain sustainable flow paths even within low-porosity crystalline basement rocks.

5.3 Sustained Permeability under Confining Pressure

Permeability measurements under confining pressure show that altered samples from the KR5 fault zone retain significant permeability even under simulated reservoir conditions (Figure 4). Permeability values only decrease from 1.6×10^{-12} m^2 at 1 MPa to 9.5×10^{-13} m^2 at 50 MPa, which corresponds to a depth of approximately 2 km. Notably, the permeability values measured at 25 MPa are comparable to those observed at depths around 819 m in the KR5 borehole ($k = 10^{-12}$ m^2). This suggests that at least some sections of these altered fault zones may retain similar hydraulic conductivity at greater depths. This implies that deep segments of such fault systems could sustain lateral fluid flow and support geothermal exploitation without significant permeability loss due to high confining pressures at depth.

The permeability values highlight that mineral alteration plays a critical role in generating a pore network capable of sustaining high permeability at industry-relevant depths of several kilometers. Data from Kivetty core samples and boreholes show that the combination of intense fracturing and strong hydrothermal alteration results in a substantial enhancement of baseline permeability. In contrast, zones characterized by fracturing, but minimal alteration, typically have permeability values only slightly higher than that of the intact rock ($k = 10^{-16}$–10^{-14} m^2), a consequence of the lack of interconnected porosity (Figure 3). This contrast shows the critical role of alteration in preserving open and well-connected flow paths under confining pressure. The observed disparity likely reflects the structurally open nature of the KR5 fault zone, where mineral dissolution and brecciation have created and maintained an interconnected void network.

6. CONCLUSIONS

This study provides new insight into how fault zones in crystalline basement rocks can act as effective geothermal reservoirs when they are structurally fractured and hydrothermally altered. The integration of field-scale hydraulic testing, high-resolution mineralogical and pore space imaging, and laboratory petrophysical analysis from the Kivetty site in Central Finland reveals that deep fault zones can sustain high permeability and pore connectivity over kilometer-scale distances and under reservoir-relevant confining pressures.

Permeability measurements on altered samples from the KR5 fault zone demonstrate that fluid flow is significantly enhanced by alteration, and is retained even under confining pressure up to 50 MPa, equivalent to depth of around 2 km. XCT imaging at an 11-micron resolution shows that pore networks remain highly connected (up to 94%) in these altered and brecciated rocks, and permeability values as high as 10^{-12} m^2 are preserved. These properties reflect extensive modifications in the rock fabric caused by prolonged hydrothermal activity involving high-temperature fluids.

The dissolution of primary minerals such as feldspars, biotite, and quartz—and the associated formation of secondary minerals like chlorite, muscovite and clay minerals—suggests that alteration occurred under relatively elevated temperatures, consistent with conditions of >200–300 °C. These processes likely took place during earlier tectono-thermal events, given the known geological history of Finland's ancient crystalline basement, where such hydrothermal systems may have remained active for extended periods. This prolonged alteration history has left behind a robust, interconnected pore network capable of maintaining high permeability under modern-day reservoir conditions.

At the reservoir scale, the long-term pumping test confirms that fluid pressure propagates laterally across distances of at least 1.5 km, indicating that the fault zone is part of a continuous and transmissive system. These results show that fracture-controlled alteration corridors can act as natural reservoirs suitable for geothermal production, potentially achieving flow rates in the order of tens of liters per second without the need for intensive stimulation.

These results have direct implications for geothermal exploration in crystalline terranes, particularly in non-volcanic, low-enthalpy regions like Fennoscandia, as well as parts of North America and Asia. In such settings, geothermal viability depends less on heat gradient and more on the ability of the rock mass to store and transmit fluids effectively, reshaping the exploration strategy for low-enthalpy geothermal resources. Targeting fractured and altered fault zones presents a promising approach for developing geothermal energy in stable continental regions, which presently are deemed too risky by the geothermal industry.

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