Fracturing and Hydrothermal Alteration in Faulted Granites: Impact on Fluid Flow and Geothermal Energy at the Kivetty Site

Daniel Carbajal-Martinez[1], Alan Bischoff[1,2], Satu Vuoriainen[1], Toni Luoto[1], Ester M. Jolis[1], Jukka Kuva[1], Jon Engström[1], Evgenii Kortunov[1], Nicklas Nordbäck[1]
[1]Geological Survey of Finland
[2]University of Turku, Finland

E-mail: daniel.carbajal@gtk.fi

This research aims to deepen our understanding of the complex interactions between mineral alterations and hydraulic conductivity in faulted crystalline rocks. It focuses on their impact on porosity, permeability, and petrophysical properties, key for defining prolific geothermal reservoirs. We observed that fracturing and mineral alterations within fault zones increase porosity (up to 20%), permeability (up to 10^{-12} m^2), and connectivity of crystalline rocks (at least 500 m sections). These discoveries highlight the potential of the Kivetty site as a valuable case study for understanding large-scale heat and fluid flow in fault zones to form amagmatic geothermal reservoirs, crucial knowledge for advancing clean energy production and heating solutions on a global scale.

Keywords: Faults zones, fracturing, hydrothermal alteration, fluid flow, geothermal energy

1. Introduction

Crystalline rocks in fault zones, altered by heat and deformation, often create favorable conditions for hosting geothermal reservoirs with high porosity and permeability (Bischoff et al., 2024). The Kivetty site, located 80 km north of Jyväskylä in the town of Äänekoski (Figure 1), provides a valuable case study for understanding the relationship between fracturing and hydrothermal alteration and their impact on large-scale hydraulic conductivity within fault zones in crystalline rocks. During the 1980s and 1990s, 13 boreholes were drilled to 250–1000 m depths to explore a nuclear waste repository, intersecting various crystalline rocks from the Central Finland Granitoid Complex (~1.8 Ga; Anttila et al., 1999). Several steeply dipping fault zones and hydrothermally altered areas were identified (Figures 1 and 2). While these structures pose a challenge to nuclear waste disposal, they present an opportunity for geothermal use due to their typical high hydraulic conductivity for fluid flow and heat. Understanding the processes that increase fluid flow is essential to unraveling the potential of geothermal reservoirs in crystalline settings and achieving sustainable energy solutions.

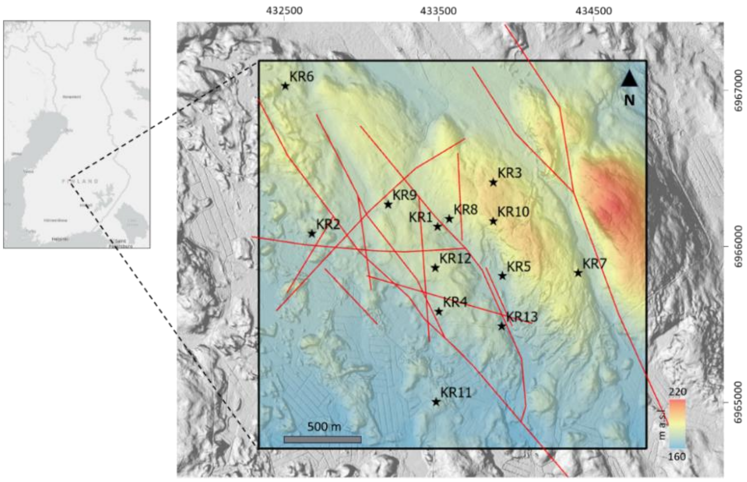

Figure 1. Location of 13 boreholes in the Kivetty site, Finland. Elevation is visualized using LiDAR data (National Land Survey of Finland, 2019), with faults marked in red lines (Anttila et al., 1999).

2. Methods and Materials

Complementing legacy studies from Posiva Oy's nuclear waste repository, we collected 92 core samples from six boreholes (KR1, KR3, KR4, KR5, KR12, and KR13) at the National Drill Core Archive of Finland. The selected samples, primarily granites and granodiorites, represent various rock facies, including massive, mylonitic, fractured, brecciated, and altered rocks. Various laboratory tests were employed at the Research Laboratory of the Geological Survey of Finland in Espoo to assess the key petrophysical properties, alterations, and fluid flow characteristics of these rocks. These techniques included petrophysical laboratory experiments (e.g., porosity, resistivity, density, elastic wave velocity, and thermal conductivity), scanning micro-XRF (µXRF) with the Advanced Mineral Identification and Characterization System (AMICS) software and computed tomography (CT scan). Additionally, hydraulic conductivity tests conducted by Posiva Oy in the boreholes at 2 m packer intervals were compared with our laboratory measurements, enhancing our understanding of the reservoir characteristics.

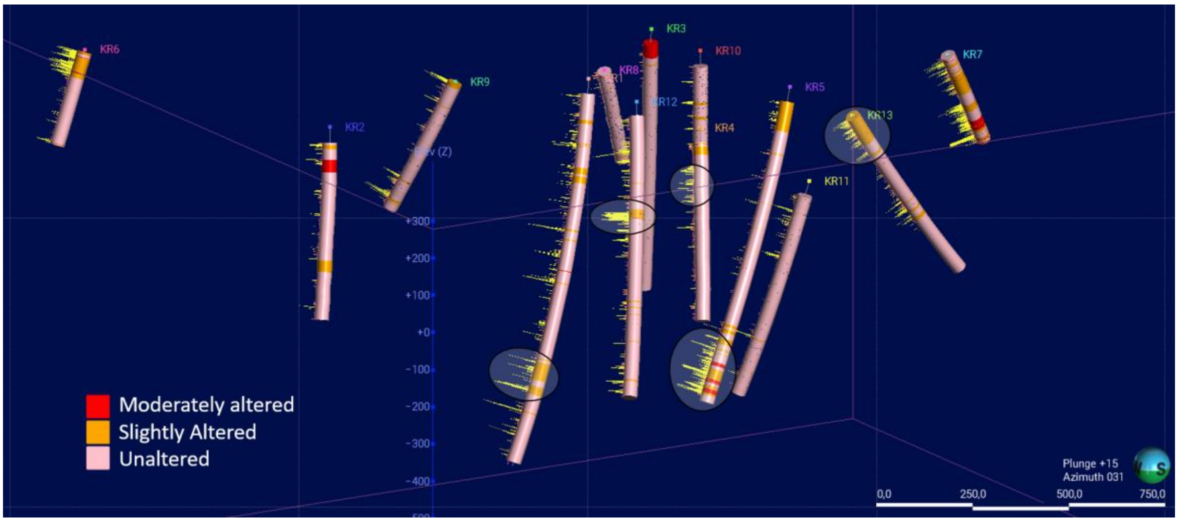

Figure 2. Directional boreholes at the Kivetty site, showing the degree of alteration and fracture frequency (yellow bars parallel to boreholes). Ovals highlight areas with high alteration and fracture frequency, indicating highly permeable connectivity zones.

3. Results and Discussion

3.1 Mineral Alteration and Petrophysical Properties

Our results show a wide range in porosity across different rock facies. Massive granites showed a low porosity (0.9%), brecciated granites exhibited a moderate porosity (9.0%), and altered granites reached a high porosity of 20% (Figure 3A). The AMICS mineralogical maps revealed that the increased porosity primarily results from the dissolution of feldspar, K-feldspar, quartz, and biotite (Figure 3A). Additionally, altered minerals, such as chlorite, epidote, Fe-oxides, Ti-oxides, and muscovite, were identified, indicating hydrothermal alteration processes at relatively high temperatures (>200 °C). These mineralogical changes significantly affect the rock properties, particularly in altered rock types. As shown in Figure 3B, higher porosity was associated with a marked decrease in density, electrical resistivity, P-wave velocity, and thermal conductivity. These changes reflect the overall alteration of the rock matrix due to the replacement of primary minerals with secondary minerals and the increase in pore spaces.

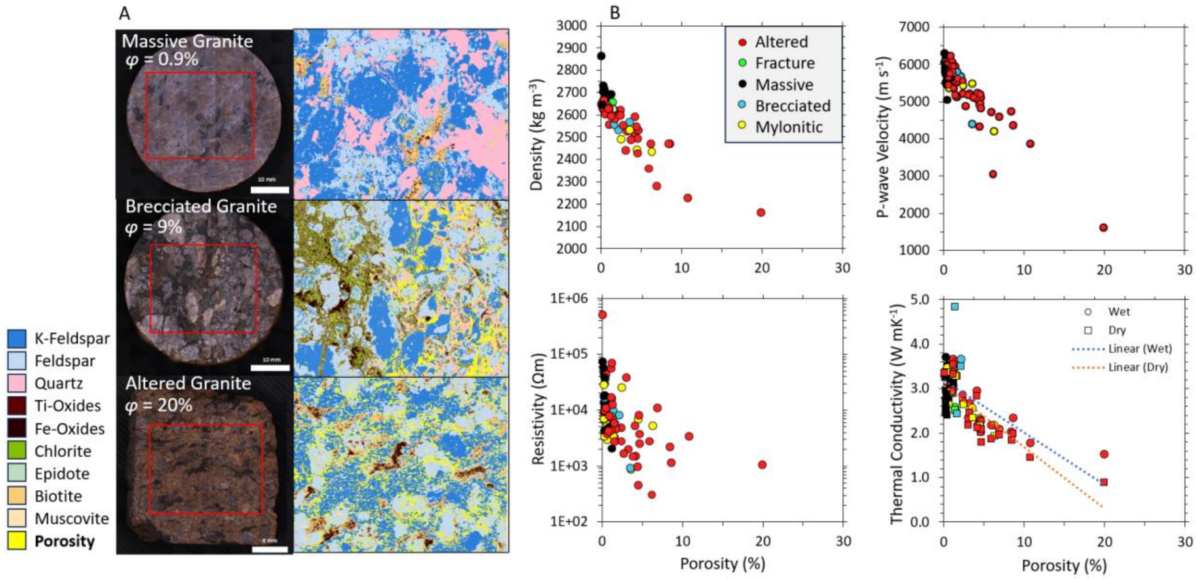

Figure 3. (A) Mineralogical maps illustrating mineral dissolution that leads to increased porosity in brecciated and altered granites. (B) Petrophysical trends show a higher porosity linked to lower density, resistivity, P-wave velocity, and thermal conductivity.

3.2 Permeability and Connectivity of Fault Zones

Hydraulic tests reveal significant permeability (k) changes across different facies, particularly between massive and altered rocks. Massive rocks have low permeability ($k = <10^{-17}$ m^2), while altered within faulted zones exhibit much higher values, approximately five times greater ($k = 1 \times 10^{-12}$ m^2 at depths of 720–850 m) (Figure 4). These structural changes, coupled to alteration and fracturing, promote enhanced fluid flow in these zones. Computed tomography scans, conducted at a resolution of 11 microns, indicate high pore connectivity of up to 94% (Figure 4) in the most altered rocks. Additionally, Posiva Oy's in situ cross-well pumping tests confirmed that these highly permeable zones are hydraulically connected over at least 500 meters sections, particularly in areas dominated by altered and fractured rocks (Figure 2; Anttila et al., 1999). This high connectivity supports the potential for extensive fluid circulation within the fault zones, enhancing the outcome of geothermal energy prospects.

3.3 Geothermal Potential within Fault Zones in Crystalline Rocks

To have a first-order estimation of the geothermal potential of these fault zones, we compare our results with the United Downs Deep Geosystems in Cornwall, UK. There, geothermal energy is extracted from a fault zone within granite, with production wells reaching temperatures of 180 °C at a depth of ~5.2 km. This site is expected to generate between 1–3 megawatts of electrical power (MWe), assuming a fault of 200 m width and a permeability of 1×10^{-13} m^2 (Ledingham & Cotton, 2021). In contrast, permeability at the Kivetty site is an order of magnitude higher than in Cornwall, and the fault width is ~100 m (Figure 4), which highlights the significant potential of fault zones to form geothermal reservoirs. Although the plumbing test depths at Kivetty and Cornwall differ, laboratory tests demonstrate that altered rocks have a minimal reduction in permeability as confining pressures increase, indicating that these rocks within fault zones can act as deep geothermal reservoirs (Bischoff et al., 2024).

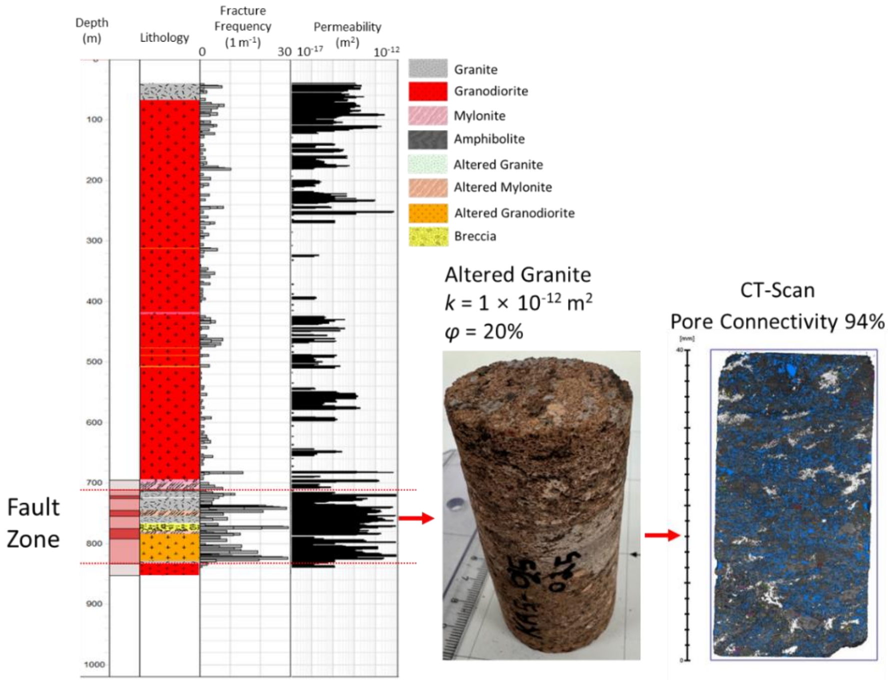

Figure 4. Borehole KR5 at the Kivetty site, Finland, showing lithology, fracture frequency, and permeability test results. The right side features a rock sample from the most permeable zone, with a computed tomography scan highlighting pore space in blue.

5. Conclusion

This study increases our understanding of the behavior of fracturing and hydrothermal alteration in the faulted granites of the Kivetty site. We found that hydrothermal alteration and fracturing significantly change the petrophysical properties of the crystalline rocks, enhancing their likelihood for deep geothermal reservoirs. While massive granite has low permeability, altered granite within fault zones shows high permeability and large-scale connectivity (at least 500 m sections) for heat and fluid flow transport, making these zones ideal sites for forming geothermal reservoirs. These findings contribute to understanding amagmatic geothermal systems within fault zones, highlighting their ideal targets in locations lacking magmatism and crustal extension, crucial information for advancing sustainable energy solutions.

6. Acknowledgement

We thank Posiva Oy and Teollisuuden Voima Oy for providing access to the Kivetty site reports.

References:

Anttila, P., Ahokas, H., Front, K., Heikkinen, E., Hinkkanen, H., Johansson, H., Paulamäki, S., Riekkola, R., Saari, J., Saksa, P., Snellma, M., Wiketrom, L., & Öhberg, A. (1999). *Final Disposal of Spent Nuclear Fuel in Finnish Bedrock - Kivetty Site Report* (Vols. 99–09).

Bischoff, A., Heap, M. J., Mikkola, P., Kuva, J., Reuschlé, T., Jolis, E. M., Engström, J., Reijonen, H., & Leskelä, T. (2024). Hydrothermally altered shear zones: A new reservoir play for the expansion of deep geothermal exploration in crystalline settings. *Geothermics*, *118*(September 2023). https://doi.org/10.1016/j.geothermics.2023.102895

Ledingham, P., & Cotton, L. (2021). The United Downs Deep Geothermal Power Project. *World Geothermal Congress*, *October*, 1–11.

National Land Survey of Finland. (2019). *Laser scanning 2008-2019 by National Land Survey of Finland*. https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/expert-users/product-descriptions/laser-scanning-data