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Crystal Clear: A Petrophysical Databank of Crystalline Rocks for Assessing Deep Geothermal Reservoirs in Fault Zones

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ABSTRACT

This study presents an extensive petrophysical dataset derived from crystalline rocks intersected by faults in Finland, collected as part of the Deep-HEAT-Flows project. Over 500 samples from outcrops and boreholes up to 2 km deep were analyzed for a range of petrophysical properties, including density, electrical resistivity, magnetic susceptibility, elastic wave velocity, porosity, thermal conductivity, and specific heat capacity. Of these, the permeability of approximately 100 samples was measured at 1 MPa, and 14 were further analyzed for permeability under confining pressures of up to 50 MPa. Standard and advanced rock characterization techniques including petrography, μ-XRF, SEM-EDS, XCT scans, XRD, and U-Pb isotope dating were used to assess mineral composition, pore morphology and connectivity, and the age of reservoir formation. Results highlight a strong link between brittle deformation, hydrothermal alteration, and enhanced reservoir properties. Porosity and permeability are often directly proportional, in which massive host rocks exhibit very low values, whereas altered and brecciated rocks collected from fault cores and damaged zones can reach up to 30% and 1.5×10^{-11} m^2 (15 Darcy), respectively. When subjected to increasing confining pressure, altered and brecciated rocks, along with fractured rocks of irregular morphology, maintain high permeability, indicating strong potential for deep geothermal reservoirs. Alongside fractures, mineral alteration and leaching of primary mineral phases create various pore types. U–Pb dating of secondary titanite indicate that porosity development in some cases dates back to Paleoproterozoic events, redefining the geothermal viability of Precambrian shields. Numerical modeling estimates that a 3.5 km-deep doublet EGS exploiting these faults could achieve above 3 MW$_{th}$ capacity over at least 50 years production. Our dataset and modeling interpretations challenge the conventional view that crystalline basement areas have low potential for reaching megawatt-scale geothermal production. On the contrary, the data demonstrate that even at modest depths of around 3.5 km, such levels of energy output are attainable.

1. INTRODUCTION

Crystalline cratons, some of the oldest and most stable geological formations on Earth, cover vast regions across Northern Europe, North America, China, and Russia. Historically, crystalline cratons have often been overlooked in geothermal exploration efforts, primarily due to the low permeability of crystalline rocks and the typically low heat flow of these regions (e.g. Achtziger-Zupančič et al. 2017; Kukkonen et al. 2023). However, with the advancement and diversification of geothermal technologies, these lower-temperature settings are being re-evaluated, particularly for their potential in direct thermal applications such as district heating and cooling and industrial use. To illustrate, the crystalline bedrock beneath Finland is estimated to store nearly 4,000,000 TWh of thermal energy at depths between four and seven kilometers—enough to meet Finland's current district heating demand for over 100,000 years (GTK 2022). Building on methods traditionally used in the oil and gas industry, our research supports this paradigm shift by elucidating the geological processes that govern the formation of fault-hosted crystalline reservoirs capable of supporting MW-scale geothermal production within stable basement cratons.

Throughout its geological evolution, the Fennoscandian Shield has undergone multiple tectonic and hydrothermal events that have generated secondary pore networks, facilitating fluid flow within its crystalline rocks. Fluid circulation in the upper crust is widely recognized as a key mechanism for heat extraction and is fundamental to the viability of large-scale (>1MW capacity) geothermal energy production (e.g. Jolie et al. 2021).

As part of the Deep-HEAT-Flows project (https://deep-heat-flows.voog.com), we are developing a comprehensive geological and petrophysical databank of crystalline rocks across Finland, evaluating their potential as deep (>1 km) geothermal reservoirs. This databank provides critical insights for assessing geothermal opportunities not only in Finland but also in comparable crystalline settings globally (Fig. 1), where tectonic and hydrothermal processes have created reservoir conditions that favor subsurface fluid flow.

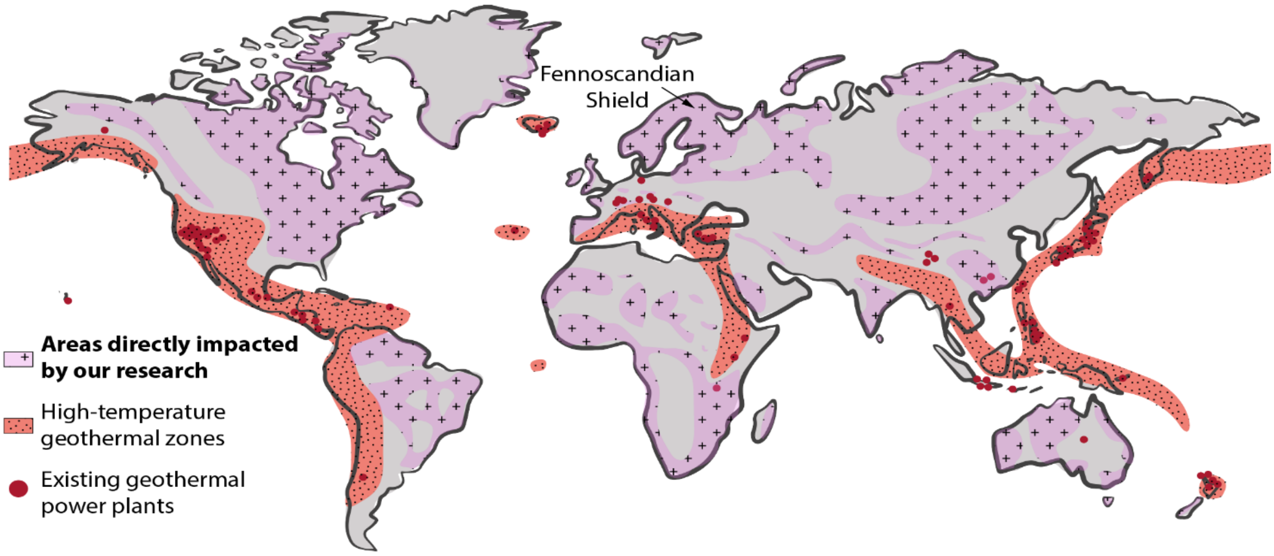

Figure 1: Simplified world geological-geothermal map highlighting the crystalline areas directly impacted by our research. Information compiled from the Global Atlas for Renewable Energy (www.irena.org/globalatlas) and the Geological Surveys Collaboration Programme (http://portal.onegeology.org/OnegeologyGlobal/).

2. METHODS

We employ a multi-scale methodological framework to investigate the formation of reservoirs in crystalline bedrock across multiple locations in Finland (Fig. 2). Over 1,500 crystalline rock samples were collected from various outcrop locations and deep boreholes, some reaching depths of about 2 km, covering diverse rock types and geological structures across the country. From this collection, approximately 500 samples were selected for laboratory experiments aiming to quantify key petrophysical properties, including porosity, bulk rock density, elastic wave velocity, thermal conductivity, specific heat capacity, electrical resistivity, and magnetic susceptibility. These 500 samples were those affected by faults, as well as samples from the adjacent host blocks. Of these, the gas permeability of around 100 samples was measured at a confining pressure of 1 MPa, and 14 were further analyzed under confining pressures of up to 50 MPa. Ongoing investigations are focused on expanding the data on permeability and porosity under increasing confining pressure. The experiments were performed on cylindrical samples with diameters ranging from 20 to 40 mm and lengths from 40 to 80 mm, at the laboratory facilities at University of Strasbourg (France) and the Geological Survey of Finland (GTK).

To complement the petrophysical analyses, we applied high-resolution rock imaging and compositional analysis techniques. Optical microscopy on 108 color-impregnated thin sections provided detailed insights into mineralogy, grain textures, alteration features, and pore morphology. X-ray computed tomography (XCT) scanning was performed on 37 samples and SEM-EDS analysis on 23 samples to generate 3D visualizations of internal rock structures and pore networks. Both low- (30 µm) and high-resolution (11 µm) scans were used to evaluate pore distribution, connectivity, and density heterogeneities. µ-XRF spectrometry was applied on 57 selected samples to generate quantitative elemental and mineralogical maps at a spatial resolution of 20 µm. Together, these methods yield an integrated petrophysical, mineralogical, and structural dataset that effectively captures the variability of reservoir properties across fault zones transecting crystalline bedrock.

Our primary focus is to characterize petrophysical variations within the structural architecture of fault zones, offering a unique dataset that delineates the reservoir properties typically associated with the fault core, damage zone, and surrounding host blocks. These data focus on crystalline rocks that have experienced brittle deformation and hydrothermal alteration, which are key processes controlling reservoir quality in these settings (Fig. 3). The rocks were classified based on their structural characteristics as massive, fractured, brecciated, and altered, as well as according to their mineralogical components. Pore types were described into categories ranging from inter-and-intra particle, moldic, vuggy, sieve, and regular and irregular fractures, enabling a systematic characterization of porosity origin and connectivity.

These data have been compiled into comprehensive spreadsheets and will be made available through various scientific publications over the course of the Deep-HEAT-Flows project, which is set to conclude in 2027. Details of the methods are reported in Bischoff et al. (2024). Based on the preliminary petrophysical data, we also perform 3D thermal–hydraulic numerical modeling using COMSOL Multiphysics software to quantify the resource potential of Enhanced Geothermal Systems (EGS) that exploit naturally permeable fault zones in low-temperature crystalline rocks.

Figure 2: Study areas include 1) Turku region, 2) Vehmaa Rapakivi Batholith, 3) Olkiluoto, 4) Porkkala–Mäntsälä Shear Zone, 5) Helsinki region, 6) Kopparnäs site, 7) Loviisa, 8) Kivetty, and 9) Koillismaa

3. PETROPHYSICAL PARAMETERS OF CRYSTALLINE RESERVOIRS

Our preliminary findings reveal a consistent trend across multiple petrophysical parameters: as porosity increases, bulk rock density, electrical resistivity, elastic wave velocity, magnetic susceptibility, thermal conductivity, and specific heat capacity tend to decrease (Fig. 4). This inverse relationship is well-documented in porous rocks (Kushnir et al. 2018) and is clearly reflected in our crystalline basement rock dataset. Furthermore, permeability generally increases as a function of porosity, both largely controlled by the degree of brittle deformation and hydrothermal alteration.

In detail, altered rocks exhibit the highest porosity and permeability, reaching up to 31.5% and 2.75×10^{-11} m^2 (27.8 Darcy), respectively. Brecciated and fractured rocks show moderate porosity (1–10%) and permeability values up to 1.96×10^{-12} m^2 (1991 millidarcy). In contrast, massive rocks—those with little or no brittle deformation and alteration—record the lowest values, with porosity below 2% and permeability less than 1.23×10^{-17} m^2. The porous and permeable rock types are primarily found within the damage zone and core of faults. In contrast, massive rocks are most commonly found within the host block, although they can also be spread throughout the fault core and damage zone.

Notably, all rocks with porosity greater than 10% are highly altered and consistently found within the fault core—a zone of intense deformation where most displacement occurs. This strongly suggests that porosity, along with related properties such as permeability, bulk rock density, electrical resistivity, elastic wave velocity, and thermal parameters, varies systematically across the architecture of faults. This pattern provides a valuable predictive framework for identifying prospective geothermal reservoirs in crystalline settings.

The suitability of crystalline rocks for geothermal energy extraction is largely governed by the morphology and connectivity of their pore networks (Duwiquet et al. 2019). As with all rock types, our dataset shows that massive crystalline rocks are characterized by sparse and poorly connected pores, which limits their reservoir potential. Their primary value in geothermal applications lies in their ability to facilitate conductive heat transfer, alongside producing heat by the decaying of radiogenic elements like uranium, thorium, and potassium. Conversely, fracture-dominated rocks generally exhibit low porosity (<5%) but can achieve exceptionally high permeability (up to 10^{-12} m^2) under low confining pressures. However, these permeability values drop sharply (down to 10^{-19} m^2) once confining pressures exceed 20–30 MPa, equivalent to depths of approximately 700–1000 meters. A different behavior is observed in altered rocks, which show only minor or negligible reduction in permeability up to the maximum confining pressure of 50 MPa (Fig 5). This indicates that only fractures with irregular, dissolution-enhanced walls, as well as brecciated and altered rocks, can sustain permeability above 10^{-16} m^2 at high confining pressures of 50 MPa, simulating depths of ~2 km. As a result, brecciated and altered rocks emerge as the most promising candidates for deep geothermal reservoirs, as they retain comparatively high porosity and permeability even under elevated confining pressure conditions.

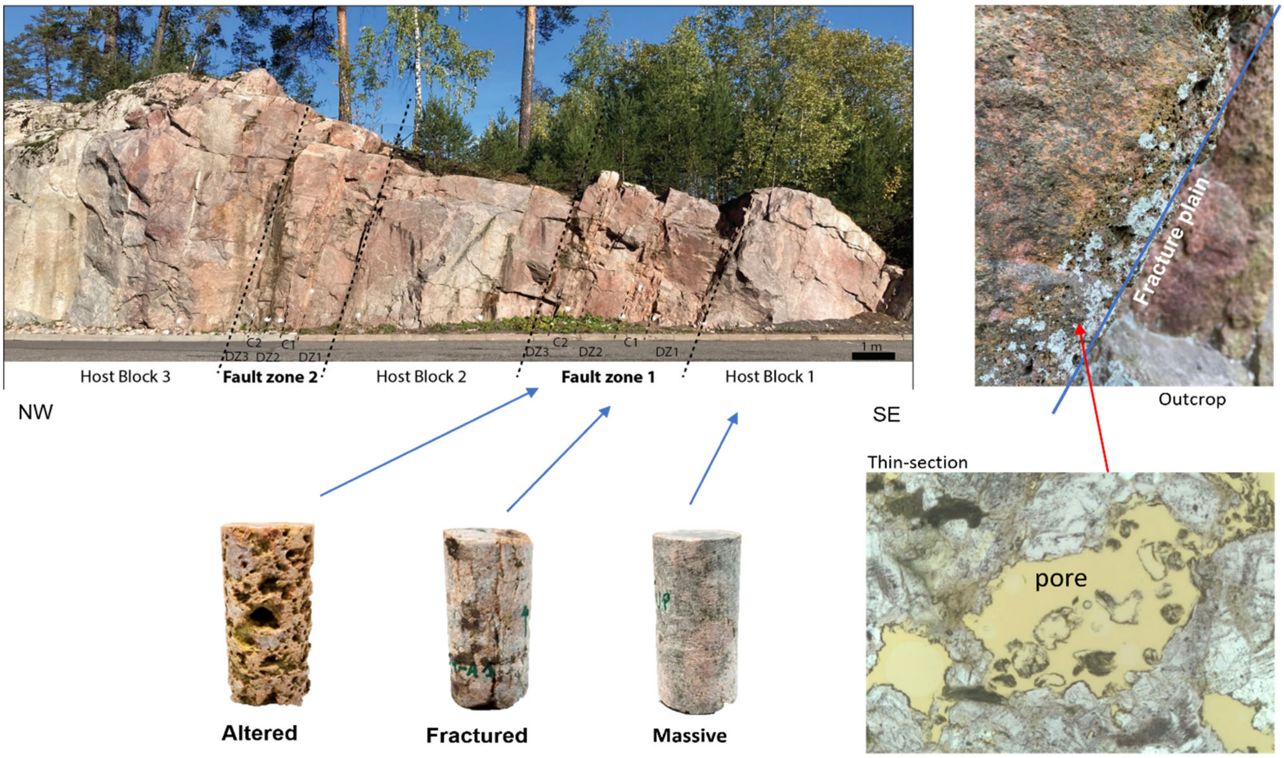

Figure 3: Architectural elements of a fault zone and their relationship to crystalline reservoir formation, as observed in an outcrop in Southern Finland.

4. CRYSTALLINE RESERVOIR FORMATION IN THE FENNOSCANDIAN SHIELD

Throughout most subsets of rocks transected by faults and fractures, a consistent pattern emerges mafic minerals such as biotite, pyroxene, and amphibole are commonly replaced by chlorite and epidote, indicating hydrothermal alteration at relatively high temperatures (200–300 °C). Additionally, feldspars and quartz dissolution also reflect alteration under similarly elevated temperature conditions above 300 °C. In altered peraluminous granites, migmatites, and gneisses, a characteristic replacement sequence of garnet → biotite → chlorite → titanite—is interpreted to reflect retrograde metamorphism and hydration of the crust (Fig 6). In certain areas near Turku, XRD analysis indicate that fractures in Paleoproterozoic migmatites are infilled with monoclinic feldspars (i.e. sanidine and orthoclase), suggesting Na-K-rich hydrothermal activity at elevated temperatures ranging around 500 °C. Similarly, regions associated with Mesoproterozoic rapakivi intrusions, such as the Suomenniemi complex within the Wiborg batholith in southeastern Finland, exhibit evidence of intense hydrothermal alteration driven by silica-undersaturated, Na-K-rich fluids. This alteration is recorded in episyenitic rocks characterized by feldspar recrystallization and the formation of clinopyroxene, with thermometric estimates indicating temperatures potentially reaching up to 770 °C (Suikkanen et al. 2019). Given the absence of major tectono-thermal events affecting the Fennoscandian upper crust in the past billion year, most faulting and hydrothermal alteration are likely of Precambrian age. To constrain the timing of porosity formation, we conducted U-Pb isotopic dating of secondary titanite at the Koillismaa site, within the Karelian Craton, Eastern Finland. The resulting age clusters at 2200–2140 Ma and 1900–1750 Ma, correspond to the Paleoproterozoic rifting of the Karelian Craton and the Svecofennian orogeny, respectively.

These mineral transformations are frequently accompanied by the development of secondary porosity. Leaching of mafic phases, feldspars, quartz, and garnet often leads to the formation of moldic, intracrystalline, and sieve-like pores, with pore connectivity typically reaching 60% and, in some cases, up to 96% at an XCT scan resolution of 11 µm (Figs. 6-8). While hydrothermal alteration and secondary porosity are dominant features throughout the dataset, the overprinting effects of weathering are also evident, particularly in samples from outcrops or shallow borehole sections (<500 m depth). These effects include interactions with meteoric water and organic fluids, contributing to further porosity modification through mineral dissolution and precipitation of iron oxide and secondary silicates and phyllosilicates at the pore walls.

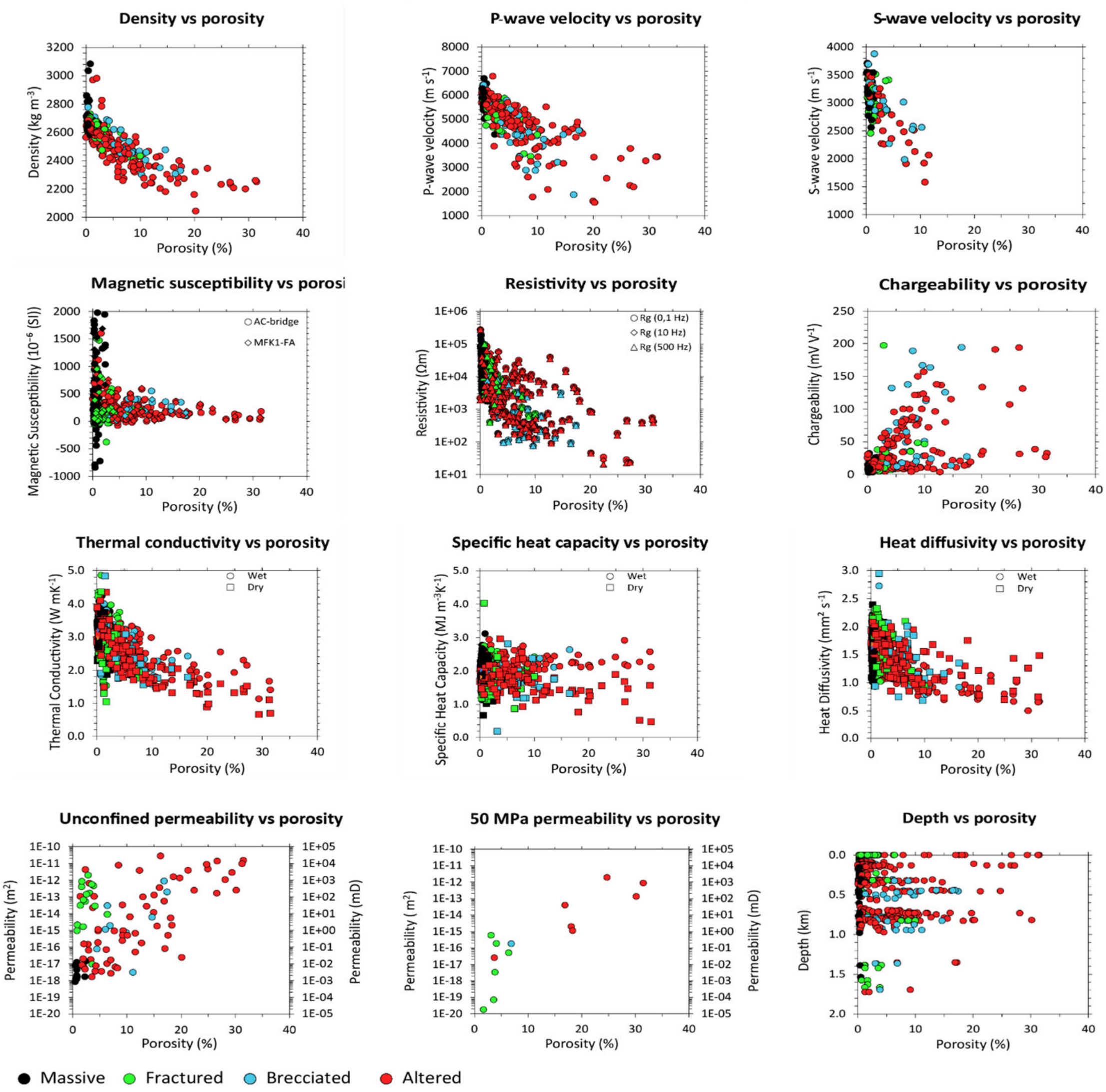

Figure 4: Petrophysical and thermal properties of crystalline rocks investigated in this study. The observed variability is primarily governed by differences in pore networks, which are largely controlled by brittle deformation processes (such as fracturing and brecciation) as well as subsequent mineral alteration.

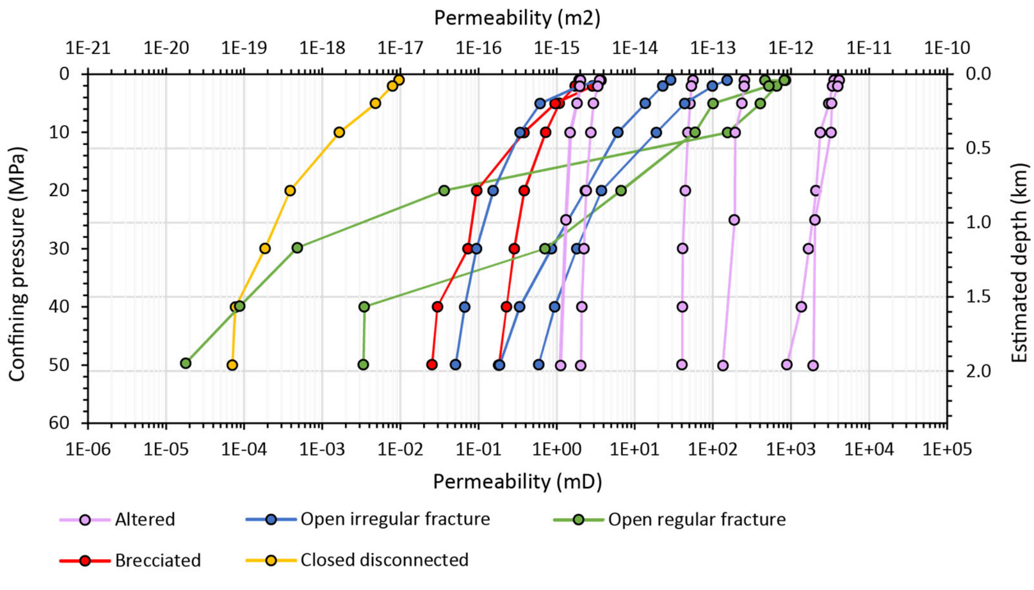

Figure 5: Permeability results from experiments conducted under increasing confining pressures. Depth estimations are based on a crystalline setting corresponding to average rock density of 2.6 g/cm³.

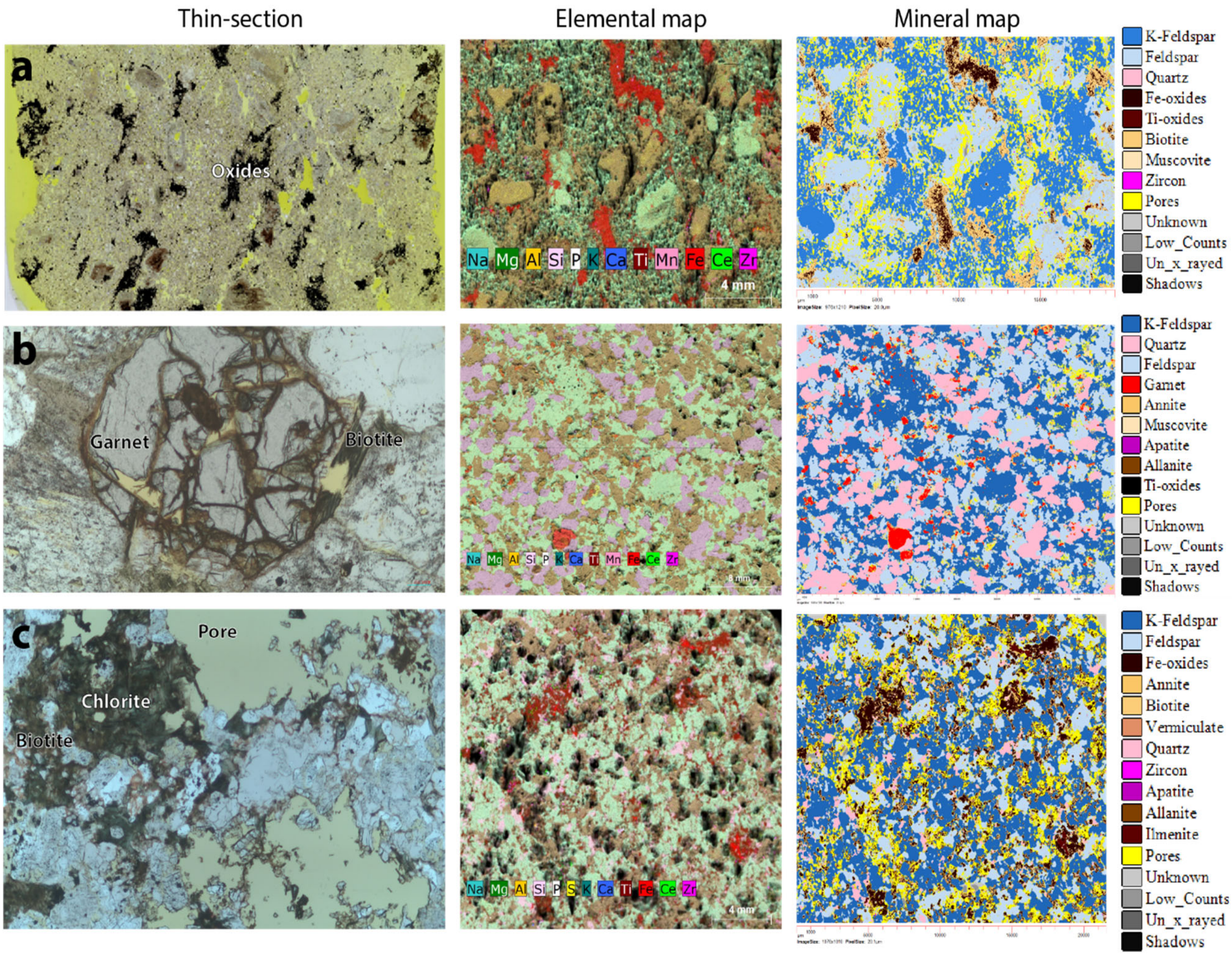

Figure 6: Examples of altered crystalline rocks as seen in thin-section microscopy, µ-XRF elemental maps, and mineral maps generated using the AMICS software.

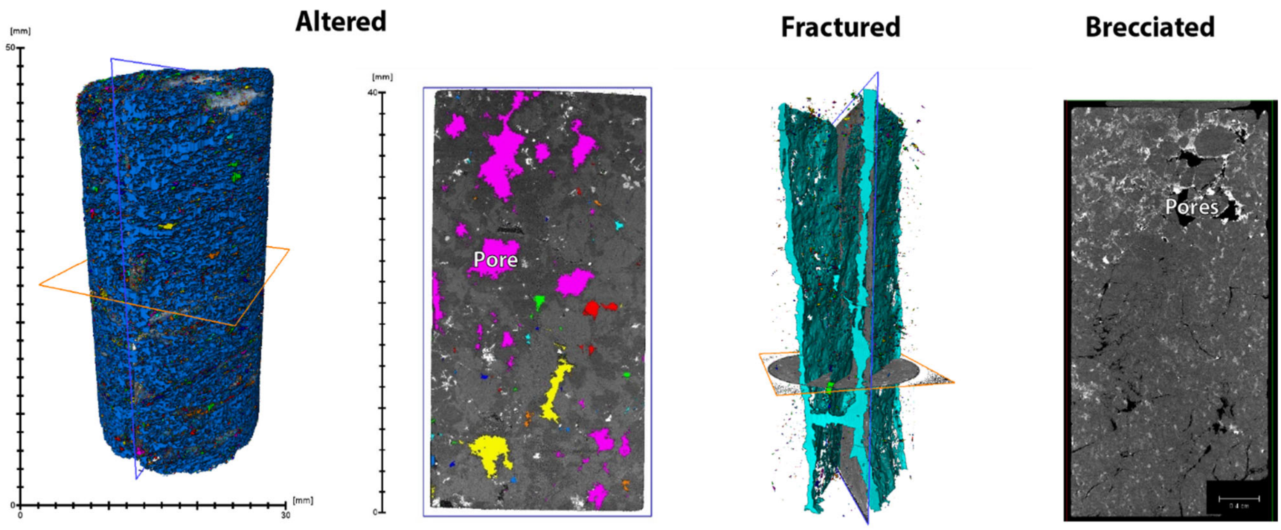

Figure 7: Examples of crystalline rocks analyzed in this study by XCT imaging and segmentation. Colors show the connected porosity of the rocks at an 11 µm resolution.

Overall, the formation of crystalline reservoirs in Fennoscandia appears to be a dynamic, multistage process involving interrelated tectonic, thermal, and chemical mechanisms. Initially, massive rocks were fractured and brecciated by tectonic or hydro-mechanical stress, generating pathways for fluid flow. Hydrothermal fluids then exploited these pathways, altering primary minerals and generating secondary porosity. Subsequent exposure to meteoric and organic fluids further reshaped this porosity through continued mineral dissolution and the precipitation of new minerals and oxides. This process may repeat over geological time as faults are reactivated under changing stress regimes or during subsequent magmatic and orogenic episodes, or due to post-glacial isostatic adjustments.

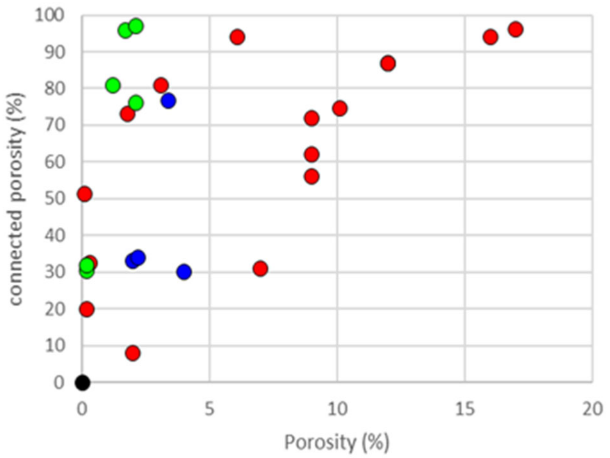

Figure 8: Plot showing the relationship between connected porosity quantified by XCT imaging segmentation at 11 µm resolution versus porosity measured at the lab with a helium gas pycnometer. The data points are color-coded as follows: black for massive rocks, blue for brecciated rocks, green for fractured rocks, and red for altered rocks.

5. IMPLICATIONS FOR GEOTHERMAL EXPLORATION IN LOW-TEMPERATURE CRYSTALLINE CRATONS

The identification of hydrothermally altered rocks as viable deep geothermal reservoirs represents a significant advancement in geothermal exploration within crystalline terrains, broadening the scope of potential targets beyond the traditional focus on volcanic and extensional settings. Our results are essential for identifying highly permeable zones within crustal-scale fault systems in otherwise low-porosity crystalline bedrock. Structural processes such as brecciation, cataclasis, fracturing, and mineral dissolution act collectively to enhance porosity and permeability, forming interconnect pore networks that can sustain fluid circulation even under high confining pressures. These naturally enhanced reservoirs, often overlooked in stable cratonic regions, challenge the assumption that crystalline rocks are universally poor geothermal targets at depth.

This approach aligns with lessons learned from geothermal projects in analogous geological contexts, yet higher-temperature settings. For example, the United Downs Deep Geothermal Power project in Cornwall, UK, has successfully targeted fracture-dominated zones within Variscan granite, demonstrating that high flow rates above 20 L/s can be achieved through natural and stimulated fracture systems in crystalline basement rocks (Reinecker et al. 2021). Similarly, the deep geothermal fields in the Upper Rhine Graben, France, particularly the Soultz-sous-Forêts and Rittershoffen sites, have shown that altered and fractured granitic basement can host productive geothermal reservoirs with capacities nearly 1.7 MW_e and 24 MW_{th} when exploiting large-scale fault zones (Frey et al. 2022).

These insights have significant implications for the development of EGS in cratonic settings like the Fennoscandian Shield, as well as similar geological contexts globally. Our findings suggest that focusing on regions naturally exhibiting enhanced permeability, resulting from a history of brittle deformation and hydrothermal alteration, could facilitate more effective soft stimulation in EGS applications (Hofmann et al. 2021). Engineering strategies could then be tailored to replicate these natural processes—through thermal, hydraulic, or chemical stimulation—aiming to enhance fracture connectivity and improve reservoir sustainability. This shift in approach opens new opportunities for low-enthalpy geothermal energy extraction in extensive crystalline regions previously deemed unsuitable, particularly where heat demand is sufficient to utilize such resources effectively.

Additionally, the extraction of valuable elements such as lithium from geothermal brines is gaining interest as a sustainable method to meet the growing demand for this critical resource. Lithium-rich brines, found in crystalline regions like France and the UK, contain concentrations often above 125 mg/L (Sanjuan et al. 2022). These geothermal waters are enriched in valuables elements due to fluid–rock reactions, a process that is also dominant in our dataset of crystalline reservoir formation. Moreover, the natural permeability of fault zones, when coupled with soft stimulation techniques, has the potential to reduce the risks typically associated with induced seismicity, thus providing a safer and more efficient method for enhancing geothermal reservoirs, provided that the pressure within the fault zones is maintained below their critical stress threshold (Hofmann et al. 2021).

6. RESOURCE QUANTIFICATION

To evaluate the influence of rock properties on the potential yield of a fault-hosted geothermal reservoir, we conducted a series of numerical simulations using COMSOL Multiphysics (Fig. 9). A 3D thermal–hydraulic numerical model was developed to simulate a doublet EGS system exploiting a permeable fault zone over a 50-year heat production period (Fig 10). The modeled system includes a fault-hosted permeable reservoir, the surrounding impermeable host rock, and a pair of geothermal wells—one for fluid injection and one for production. The reservoir geometry was based on fault structures observed in crystalline bedrock settings in Finland (e.g. Koillismaa, Kivetty, and

Kopparnäs areas; Fig. 2) and simplified in the model as a tabular, 100-meter-thick fault zone dipping 70°. The injection well was placed at a depth of around 2.6 km and the production well at 3.5 km, with a total well spacing of 1 km along the plane of the reservoir. For model simplicity, only the well sections within the permeable reservoir are included into the calculations, and heat loss from the ascending fluid within the wellbore was calculated separately. Heat transfer was modeled across the entire 3D block, including a ~0.5 km^3 reservoir section, with model boundaries set far enough to avoid influencing the simulation results. Fluid flow was calculated using Darcy's law, considering only the reservoir section, while the host rock was assumed to be impermeable. Thus, the impermeable host block only considers conductive heat transfer while both conductive and convective heat transfer was calculated only for the reservoir section.

The initial geothermal conditions were defined using a heat flux of 40 mW/m^2 and typical geothermal gradient of Southern Finland bedrock (Piipponen et al. 2022). Petrophysical parameters such as rock density, porosity, thermal conductivity, and specific heat capacity were assigned based on average values derived from our dataset of massive, fractured, brecciated, and altered rocks (Table 1; Fig. 4). In this preliminary model, only average petrophysical values were considered, with future work planned to incorporate the top and bottom 10th percentiles for more accurate sensitivity analysis. The permeability of each rock class was defined as a function of depth and extrapolated to 4 km using our laboratory results from confining pressure experiments (Fig. 5). Other thermo-hydraulic parameters, such as the fluid injection temperature and flow rate, were set to 5°C and 20 L/s, respectively. The flow rate was selected as the lower range of expected values for a permeable fault zone transecting crystalline rocks, based on cross-flow tests from the Kivetty site and alike geothermal reservoirs in the Upper Rhine Graben and Cornwall (Reinecker et al. 2021; Frey et al. 2022).

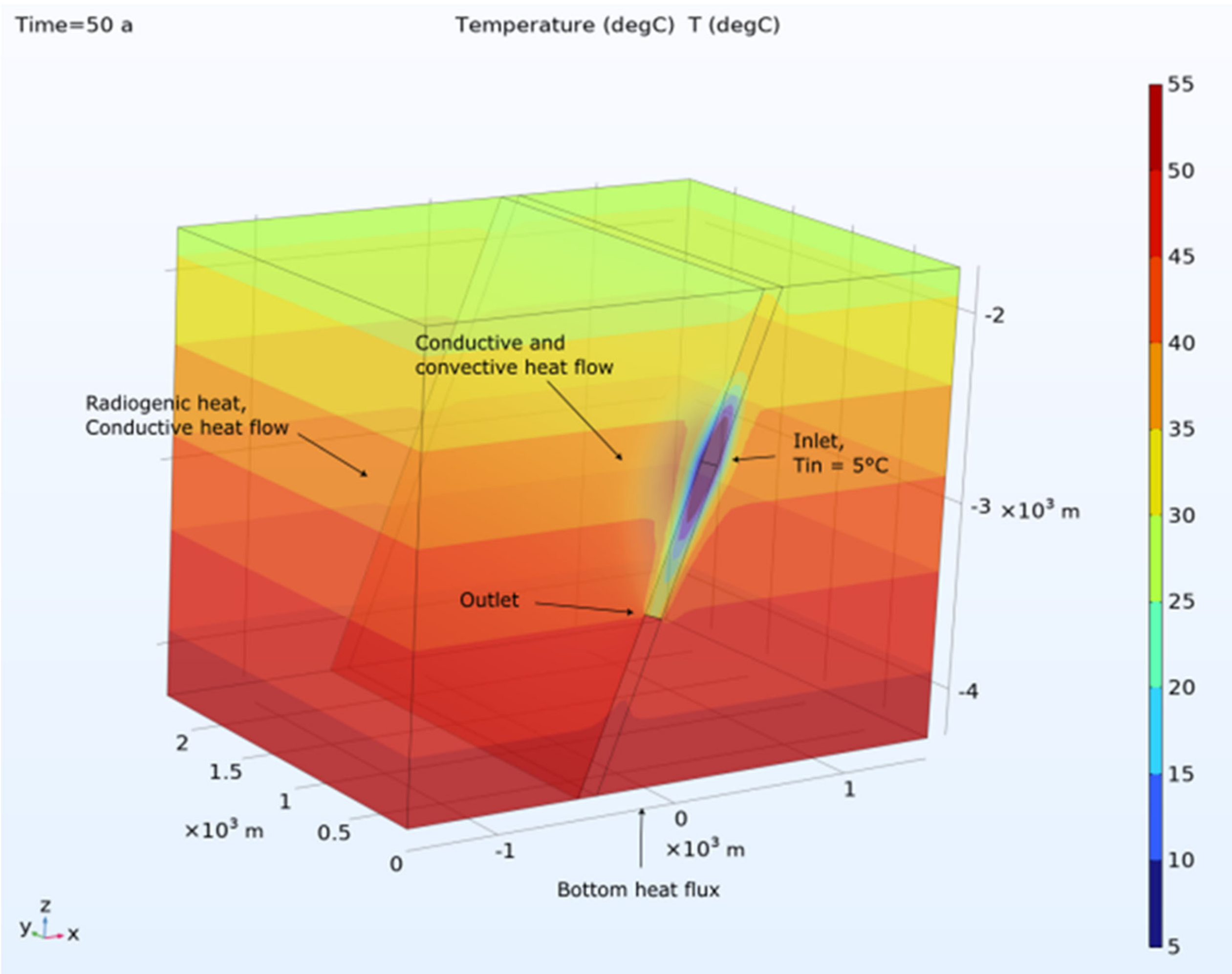

Figure 9: Schematic visualization of a 3D thermal–hydraulic model idealized for a doublet EGS system exploiting a permeable fault zone. The block diagram illustrates the evolution of a cold plume migrating from the injection well (inlet) toward the production well (outlet) after 50 years of operation. Rainbow colors represent the modeled temperature distribution within the fault zone and its surrounding host rock.

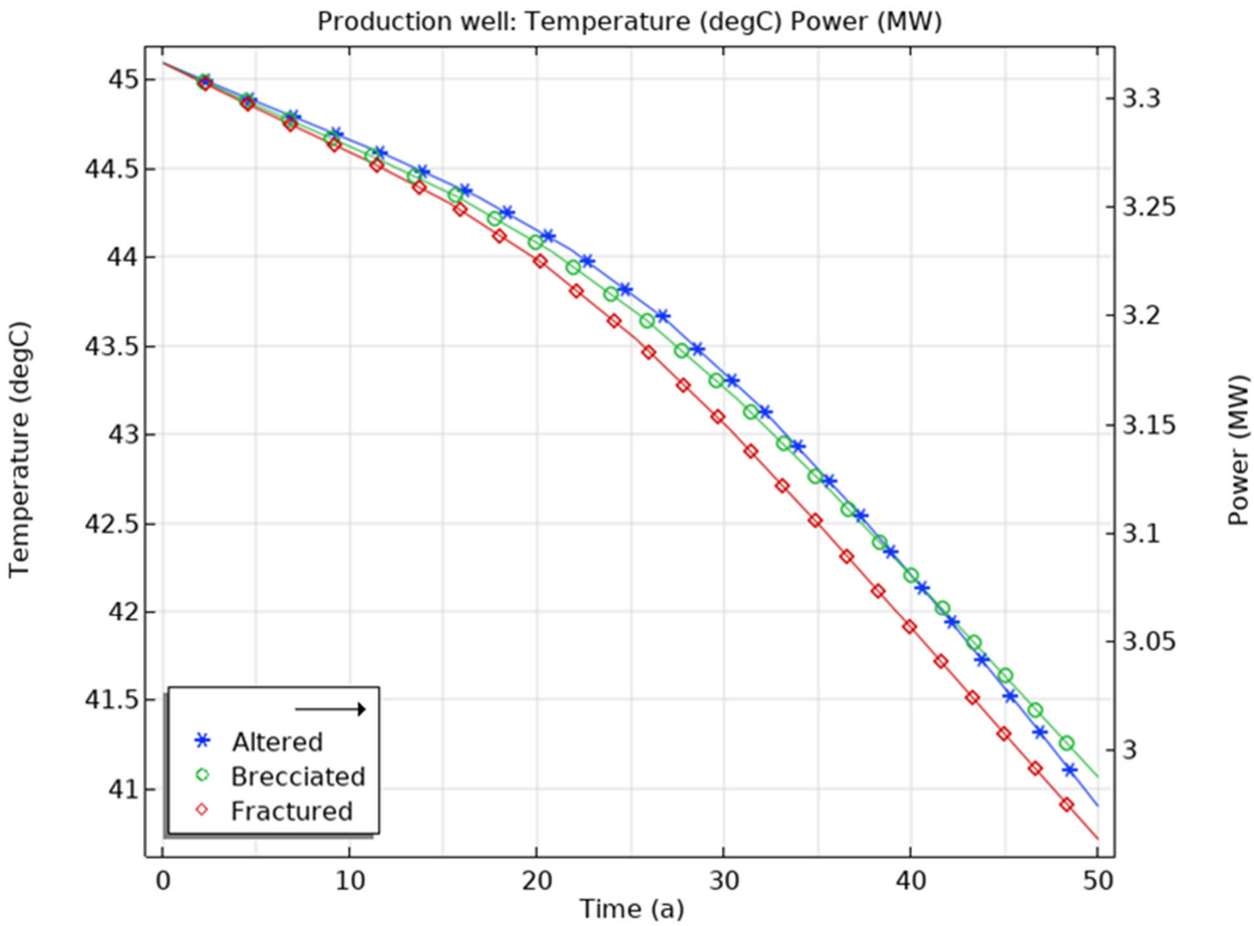

Figure 10: Simulated thermal power output for different reservoir types (fractured, brecciated, and altered) over a 50-year production period.

Table 1: Average petrophysical and thermal parameters of each rock type used in the numerical model.

Rock type	Number of Samples	ρ (kg/m³)	ϕ (%)	λ (W/m k)	C_p J/kg K
Altered	82	2467	9.5	2.6	852
Brecciated	21	2526	6.3	2.9	805
Fractured	43	2615	1.8	3.0	817
Massive	42	2650	0.5	3.25	779

Our results indicate that a 3.5 km deep doublet EGS constructed within a permeable fault zone can yield a thermal power capacity ranging from 2.9 to 3.3 MW_{th} over 50 years of operation (Fig. 10). Notably, the outlet temperature decreases only slightly—from 45 °C to 41 °C—over the 50-year simulation, indicating minimal thermal breakthrough in the reservoir. This contrasts sharply with closed-loop geothermal technologies, which often experience a rapid temperature decline within the first few months to years of operation (Piipponen et al. 2022). Additionally, all reservoir types (i.e. fractured, brecciated, and altered) show remarkably similar thermal performance, irrespective of their petrophysical discrepancies. This finding should be further investigated using more robust thermo-hydro-mechanical-chemical (THMC) simulations that account for dynamic flow rate outcomes and potential geo-chemo-mechanical feedbacks during long-term operation. In the next phase of the project, we plan to incorporate these parameters in our models, and validate them against real-world data from the Cornwall geothermal sites.

7. CONCLUSIONS

This study demonstrates the geothermal potential of faulted crystalline rocks in Finland, revealing a consistent pattern of enhanced porosity and permeability within zones of brittle deformation and hydrothermal alteration. Our integrated petrophysical dataset shows that altered and brecciated rocks found within the core and damaged zone of faults maintain high permeability even under confining pressures up to 50 MPa, making them viable targets for deep geothermal reservoirs. Notably, a consistent mineralogical trend is observed across altered rock subsets: mafic minerals such as biotite, amphibole, and pyroxene are replaced by chlorite and epidote, indicating hydrothermal alteration at 200–300 °C. Feldspar and quartz dissolution suggests fluid activity above 300 °C, while certain migmatites and granites display retrograde metamorphic sequences such as garnet → biotite → chlorite, reflecting deep crustal hydration. In Paleoproterozoic migmatites near Turku, fracture infill of sanidine and orthoclase indicates Na-K-rich fluids active at ~500 °C. Even higher hydrothermal alteration events reaching of up to ~770 °C are inferred in episyenitic rocks of the Wiborg Batholith, linked to Mesoproterozoic rapakivi magmatism and generation of secondary porosity. U–Pb dating of secondary titanite from the Koillismaa site constrains porosity formation to 2200–1750 Ma, aligning with Paleoproterozoic rifting and the Svecofennian orogeny. These findings suggest that reservoir-quality properties in the Finnish crystalline basement are largely inherited from Precambrian tectono-hydrothermal events. Our data and simulations demonstrate that EGS systems targeting permeable fault zones at ~3.5 km depth can sustain thermal capacity of approximately 3 MW_{th} over a 50-year production period. These findings highlight the potential of Precambrian crystalline shields to contribute to substantial, commercially viable geothermal energy production, challenging the previous assumption that they are unsuitable for MW-scale geothermal projects.

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