Crystal clear: A petrophysical databank of crystalline rocks for assessing deep geothermal reservoirs in Finland and beyond

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We performed multiple laboratory experiments and analytical techniques to define the petrophysical characteristics and understand the formation of deep crystalline reservoirs in Finland. Our results indicate that fracturing and mineral dissolution can create exceptional reservoirs with porosity and permeability values of up to 31.5% and 1.5 × 10^{-11} m^2 (15.2 Darcy), respectively. Hydrothermal alteration and tectonic processes are responsible for the formation of these reservoirs, which must date back to Precambrian times. Our findings could represent a significant shift in geothermal exploration within ancient crystalline cratons, expanding target prospects beyond the conventional focus on volcanic and rifting areas.

Keywords: crystalline reservoirs, geothermal energy, petrophysics, hydrothermal alteration

1. Geological background and geothermal opportunities

Finland's crystalline bedrock consists of various Precambrian igneous, metamorphic, and supracrustal rocks that typically exhibit low porosity and low permeability. Consequently, these rocks have little reservoir potential mainly due to the interlocking nature of their minerals typically formed under or rearranged at high pressure and temperature conditions. However, during its geological evolution, the Finnish crystalline crust experienced multiple tectonic and hydrothermal events that created secondary pore networks (Figure 1), enabling fluid flow within these rocks. The circulation of fluids in the upper crust is widely known as one of the main drivers facilitating heat extraction and the development of geothermal energy prospects (e.g. Jolie et al. 2021). As part of the Deep-HEAT-Flows project (https://deep-heat-flows.voog.com), we are compiling a comprehensive geological and petrophysical databank for crystalline rocks across Finland, evaluating their potential as deep (>1 km) reservoirs. Our databank will provide valuable information for assessing geothermal opportunities in Finland and in similar crystalline settings affected by tectonic and hydrothermal activity.

2. Methods

Our investigations involve a range of laboratory-based experiments, including measurements of rock density, elastic wave velocity, electrical resistivity, magnetic susceptibility, porosity and permeability under various confining pressures, and thermal properties of over 300 samples of crystalline rocks collected from diverse outcrop locations and boreholes across Finland. Additionally, we employ detailed mineral and pore space characterization techniques, including thin-section petrography, micro-XRF spectrometry, SEM-EDS, X-ray CT scans, and isotope dating, to better understand the processes that control the formation of crystalline reservoirs. Our focus is on defining petrophysical variations in the architecture of fault zones, offering a unique dataset that details the characteristics and reservoir properties typically found in the fault core, damage zone, and host blocks of crystalline rocks subjected to brittle deformation and hydrothermal alteration. This information has been compiled into comprehensive spreadsheets and will be made available through various scientific publications over the course of the project, which is set to conclude in 2027.

3. Petrophysical parameters of crystalline reservoirs

Our preliminary findings highlight a consistent trend among various petrophysical parameters: rock density, electric resistivity, elastic wave velocity, magnetic susceptibility, thermal conductivity, and heat capacity typically decrease as porosity increases (Figure 2), a pattern classically observed across sedimentary and volcanic rocks. Additionally, porosity and permeability are usually directly proportional and governed by the extent of brittle deformation and alteration processes affecting the crystalline rocks. Thus, altered rocks have the higher porosity and permeability values, up to 31.5% and 1.5×10^{-11} m^2 (15.2 Darcy), respectively; brecciated and fractured rocks have moderate porosity ranging from 1 to 10% and permeability up to 8.38×10^{-13} m^2 (849 millidarcy); while massive rocks recorded the lowest porosity (<2%) and permeability ($<1.23 \times 10^{-17}$ m^2) values. Markedly, these rocks are consistently distributed across diverse parts of fault zones. Typically, altered, brecciated, and fractured rocks are found in the fault core and damage zone, while massive rocks occur within the host block. However, massive rocks can also occur in the damage zone and fault core. Notably, all rocks with porosity above 10% are highly altered and consistently located within the fault core, a zone characterized by intense deformation where most of the fault displacement occurs. This observation highlights that porosity (and consequently other properties such permeability, density, resistivity, elastic wave velocity, and thermal parameters) systematically varies following the fault architecture, providing a valuable prospective model for locating geothermal reservoirs in crystalline settings. In detail, the quality of crystalline reservoir (i.e. their suitability for geothermal energy extraction) is primarily revealed by the morphology and connectivity of diverse pore types (Bischoff et al. 2024). Massive rocks typically have dispersed and disconnected pores and thus have little reservoir potential. Their value in geothermal systems relies on their ability to store and transfer heat by conduction, due to abundant minerals such as quartz and feldspar, as well as to generate heat through the decay of radioactive elements like uranium, thorium, and potassium. Conversely, rocks dominated by fractures typically have low porosity (<5%) but can exhibit extremely high permeability (nearly 10^{-12} m^2) at low confining pressure, which sharply decreases to 10^{-19} m^2 when confining pressure exceeds 20–30 MPa, corresponding to depths of around 700–1000 meters. According to our dataset, only fractures with irregular walls commonly resulting from mineral dissolution and brecciation can sustain permeability above 10^{-16} m^2 at high confining pressures of 50 MPa, simulating depths of approximately 2 km. Consequently, rocks that have undergone brecciation and hydrothermal alteration are the most promising deep geothermal reservoirs because they show comparatively milder porosity and permeability reduction even under high confining pressures of 50 MPa.

4. Crystalline reservoir formation in Fennoscandia

Throughout most subsets of rocks transected by faults and fractures, a consistent pattern emerge: mafic minerals including biotite, pyroxene and amphibole are commonly replaced by chlorite and epidote, indicating hydrothermal alteration processes at relatively high temperatures (200–300 °C). Additionally, altered peraluminous granites, migmatites and gneisses display a replacement order of garnet→biotite→chlorite→titanite, which is consistent with retrograde metamorphism and hydration also at relatively high temperature. We observe that the effects of hydrothermal alteration and leaching of mafic mineral phases, plagioclase, and garnet are often associated with the generation of secondary porosity. This includes the development of moldic, intracrystal, and sieve pores, typically achieving 60% and up to 96% pore connectivity at an 11 µm CT scan resolution. As thermal and tectonic events of great magnitude have not been reported to substantially affect the Fennoscandian upper crust in the last billion years, most faulting and hydrothermal alteration must date from Precambrian times. We perform U-Pb isotope dating of secondary titanite to serve as a proxy for the age of porosity formation at a location in the Karelian Craton. The age results cluster at 2200-2140 Ma and 1900-1750 Ma, confirming a temporal correlation with the Paleoproterozoic rifting of the Karelian Craton and the Svecofennian orogeny. Although the relationship between hydrothermal alteration and secondary porosity exerts a first-order control throughout our dataset, the overprinting effects of weathering due to the exposure of the crystalline rocks to meteoric water and organic fluids is also commonly observed, particularly in rock samples collected from outcrops or from shallow (<500 m) borehole sections. In light of our observations, we describe the formation of crystalline reservoirs as a dynamic process that likely involves multiple interrelated tectonic, thermal, and chemical stages: Initially, massive rocks were fractured and brecciated by tectonic forces or hydro-mechanical stress, creating pathways for fluid circulation. Hydrothermal fluids then use these fracture pathways and interact with primary minerals, inducing chemical alterations and leaching, which lead to the generation of secondary porosity. When finally exposed to meteoric and organic fluids, the porosity initially created at higher temperature conditions is further reshaped by additional mineral dissolution processes and the precipitation of new mineral phases and oxides. These processes can be repeated multiple times as faults are reactivated under new stress regimes or during younger magmatic and orogenic events.

5. Implications for geothermal exploration

The identification of hydrothermally altered rocks as potential deep geothermal reservoirs could represent a significant shift in geothermal exploration within crystalline regions, expanding target prospects beyond the conventional focus on volcanic and rifting areas. Our results are crucial for identifying highly productive permeable zones within crustal fault transecting crystalline terrains. Brecciation, cataclasis, fracturing, and mineral dissolution collectively contribute to the creation of exceptional reservoir properties, which have been widely overlooked in deep setting of crystalline cratons. Additionally, our results have the potential to support the advancement of Enhanced Geothermal Systems, which could prioritize creating more intricate fracture networks through thermal and chemical stimulation, mimicking the natural formation of crystalline reservoirs in the Fennoscandia Craton.

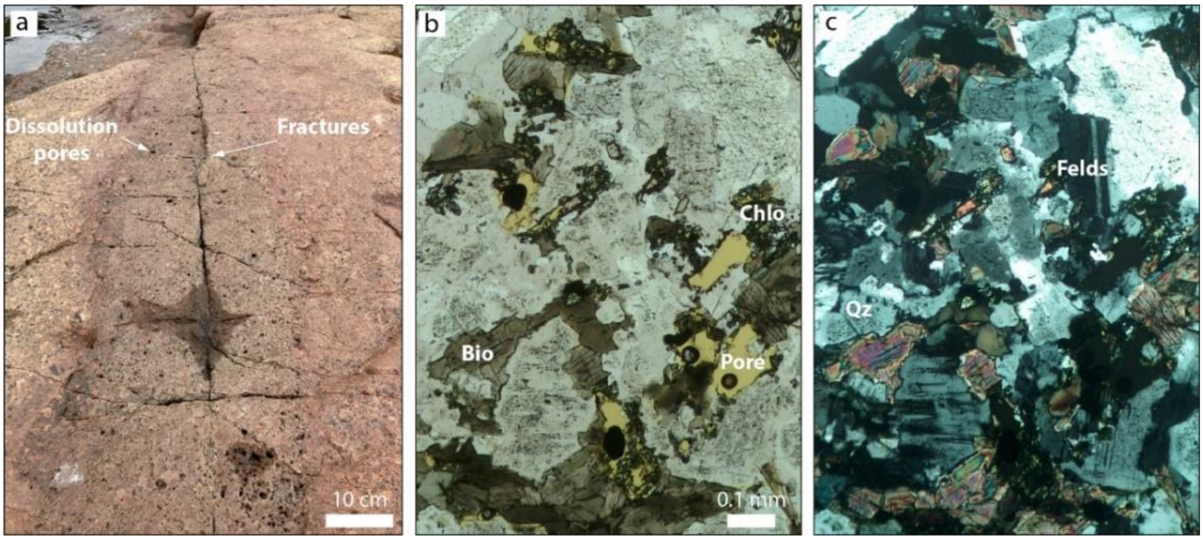

Figure 1. Examples of crystalline rocks affected by fracturing and hydrothermal alteration. (a) Rapakivi granite from the Vehmaa Batholith, Southern Finland. Microphotographs in natural (b) and plain polarized light (c) of an altered granite collected from a depth of 1620 m from the Koillismaa borehole, Eastern Finland.

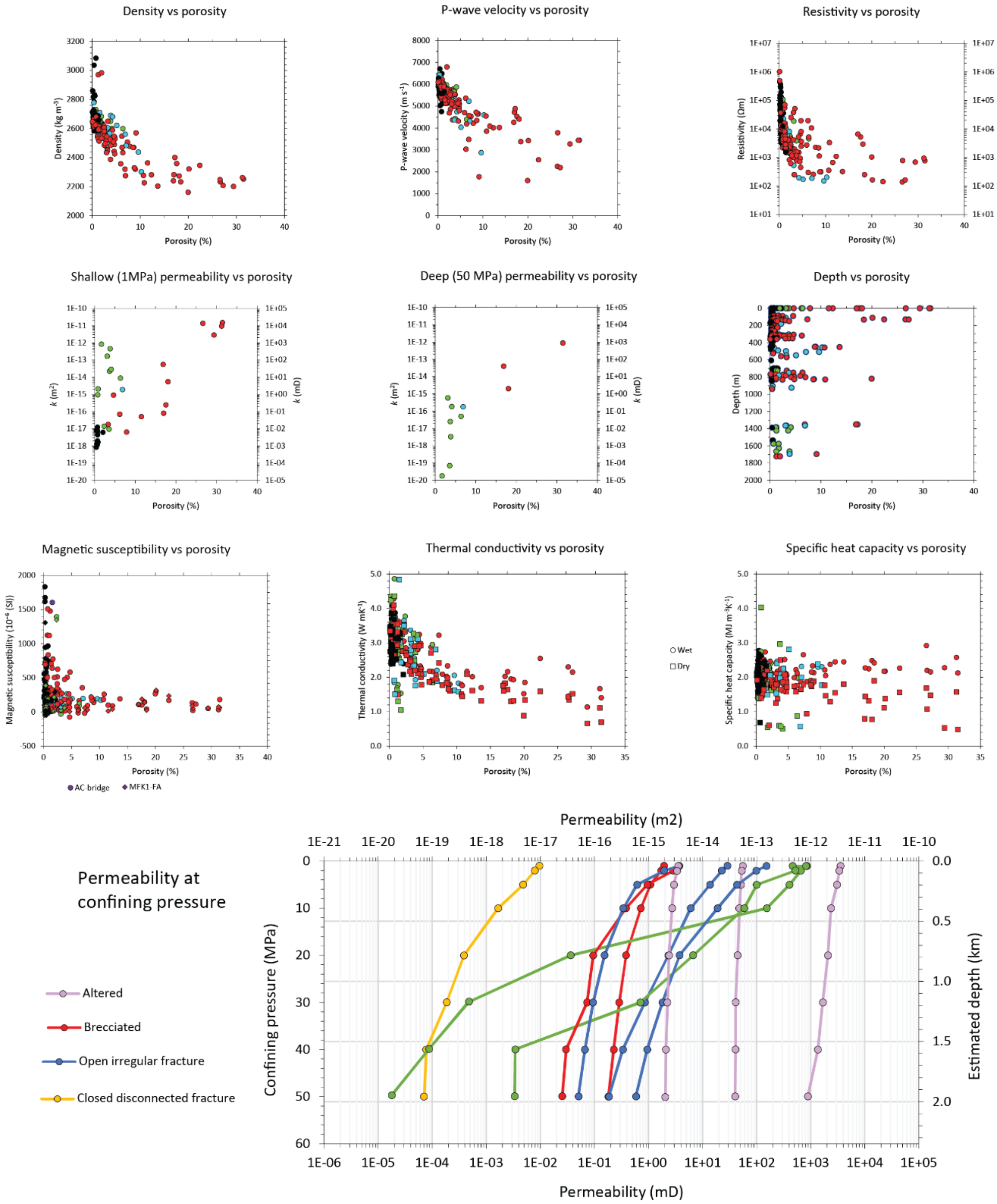

Figure 2. Main petrophysics trends observed on Finnish crystalline rocks, sorted by their texture and structure. Black dot = massive; green = fracture; blue = brecciated; red = altered.

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