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

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This study explores the impact of fracturing and hydrothermal alteration on porosity, permeability, and fluid dynamics in faulted crystalline rocks at the Kivetty site, Finland. Understanding these processes is essential for identifying key factors in geothermal reservoir formation, especially in crystalline basement settings away from volcanic or rifting activity. We focus on how brittle deformation and mineral alteration in fault zones affect the petrophysical properties of crystalline rocks, which directly influence geothermal reservoir potential. We analyzed 92 core samples, primarily granites and granodiorites, from six boreholes up to 1 km deep. A multidisciplinary approach was employed, including benchtop petrophysical measurements (density, electrical resistivity, elastic wave velocity, thermal conductivity), permeability and porosity testing under varying confining pressure, petrographic analysis, scanning micro-XRF using the Advanced Mineral Identification and Characterization System software, X-ray computed tomography (CT), and legacy data from in situ cross-well hydraulic pumping data. Our findings show that altered and fractured rocks significantly enhance fluid flow connectivity, extending laterally for at least 500 m. Hydrothermal alterations, dominated by the dissolution of feldspar, K-feldspar, quartz, and biotite, and the precipitation of chlorite, epidote, Fe-oxides, Ti-oxides, and muscovite, suggest formation under high temperatures (exceeding 200 °C), with overprinted lower-temperature meteoric alteration. These alterations increase porosity (up to 20%) and permeability (up to 10^{-12} m^2) in fault zones, with pore connectivity up to 94% as measured by CT scans at 11-micron resolution. In contrast, unaltered host rocks exhibit much lower porosity (~1%) and permeability ($<10^{-17}$ m^2). Moreover, the altered rocks show minimal porosity and permeability reduction under confining pressure corresponding to depths of up to 2 km, indicating the potential for geothermal fluid circulation at industry-relevant depths. This increase in porosity reflects significant alteration of the rock matrix, leading to decreased density, electrical resistivity, and elastic wave velocity, while enhancing thermal conductivity in wet conditions. These findings demonstrate that fault zones significantly enhance porosity, permeability, and connectivity pathways, which are critical for efficient heat and fluid transport in geothermal systems. This study advances the understanding of fluid flow in faulted crystalline rocks affected by brittle deformation and mineral alteration, offering insights for optimizing deep geothermal reservoirs for sustainable energy production.