Strike-Slip Faulting and Hydrothermal Alteration in the Vehmaa Rapakivi Batholith: Insights into Reservoirs in Crystalline Rocks and Geothermal Potential in Southern Finland

Nicklas Nordbäck[1], Alan Bischoff[12], Kaisa Nikkilä[3], Daniel Carbajal-Martinez[1], Jon Engström[1], Pietari Skyttä[4], Andy Nicol[5], Nikolas Ovaskainen[1], and Steffi Burchardt[6]

[1]Geological Survey of Finland
[2]University of Turku, Finland
[3]Åbo Akademi University, Finland
[4]Structural Geology Company, Finland
[5]University of Canterbury, New Zealand
[6]University of Uppsala, Sweden
D6ing7
E-mail: nicklas.nordback@gtk.fi

Here we report on brittle deformation and post-magmatic hydrothermal alteration within the rapakivi granites of the Vehmaa Batholith, Southern Finland. We observed that mineral alteration and porosity are structurally controlled and mainly occur in association to NW–SE striking faults along precipitation of mineral assemblages typical of hydrothermal processes. The results of fault kinematic paleostress suggest two stages of Proterozoic strike-slip faulting, as previously interpreted from the Åland rapakivi. Our new results advance the understanding of the brittle deformation and thermal evolution of the Fennoscandian crust during the Meso–Neoproterozoic, providing valuable insights into the potential of crystalline rocks as geothermal reservoirs within granitic settings.

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

1. Rationale

Reservoirs in crystalline rocks are typically formed by post-emplacement tectonics and hydrothermal activity, which can result in fracturing and dissolution pore networks. Ancient crystalline terranes, such as the Fennoscandian Shield, often experience multiple tectonic and magmatic events, leading to a complex history of fault reactivation and hydrothermal activity that can be challenging to unravel. The emplacement of rapakivi granites during the Paleo–Mesoproterozoic marks the end of a series of major orogenic and magmatic events in Southern Finland. Consequently, their anorogenic character and limited post-emplacement tectonic deformation provide an ideal setting for studying the mechanisms resulting in crystalline reservoir formation. To enhance understanding of these unconventional reservoirs, we investigate the effects of brittle deformation and hydrothermal alteration in the Vehmaa rapakivi Batholith, Southwest Finland.

2. Methods

We employed a multiscale approach including regional-scale lineament interpretation from magnetic and electromagnetic aerogeophysical maps (Hautaniemi et al., 2005), LiDAR data (National Land Survey of Finland, 2019) and bathymetric data (EMODnet Bathymetry Consortium, 2018). Mesoscale (meters to hundreds of meters) interpretation involved drone photogrammetry, fieldwork, and paleostress analysis, while at the microscale (mm to cm), we conducted microscopic petrography and petrophysical laboratorial tests from key lithologies.

3. Characterization of brittle structures within the Vehmaa Batholith

Our 1:200 000 scale lineament analysis of the Vehmaa rapakivi granite revealed two main sets of lineaments with NNW and ENE trends, which contrast with the regional NNE orientation of major lineaments within the surrounding Paleoproterozoic bedrock (Figure 1). The NNW lineaments are relatively continuous over several kilometers, while the ENE lineaments typically terminate against the NNW lineaments, suggesting that the ENE lineaments are younger.

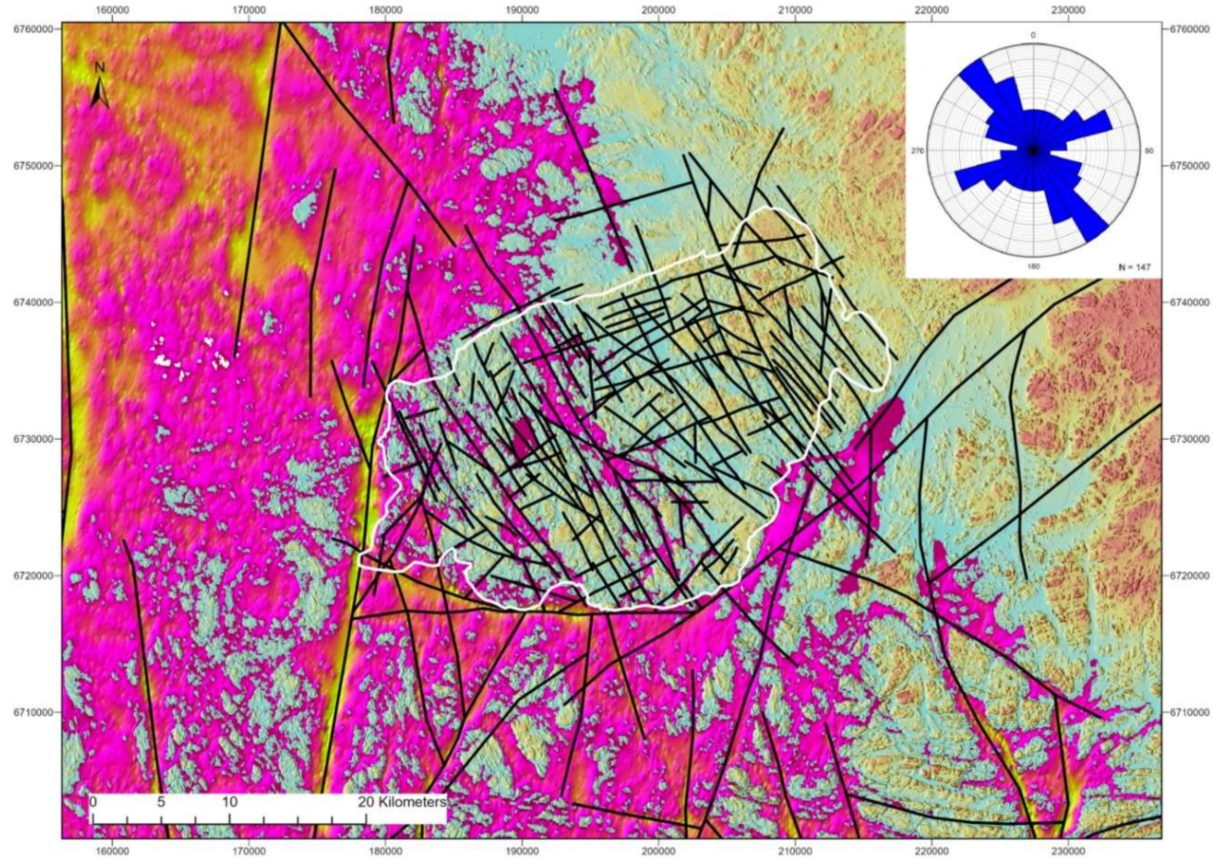

Figure 1. The regional-scale lineaments as interpreted on integrated geophysical and topographic data. Lineaments were interpreted at a 1:200 000 map scale within the Vehmaa Batholith (outlined in white), while a 1:500 000 map resolution was used for extending and interpreting the major lineaments of the surrounding areas. Rose plot displays lineament strikes within the batholith. Source rasters comprise LiDAR (blue-red colour scale) and bathymetry data (yellow-magenta colour scale).

In outcrop and drone photogrammetry, faults and fractured zones extend over tens to hundreds of meters and aligning consistently with the location and orientation of larger lineaments. The most prominent fault sets exhibit NW trends and strike-slip character (Figure 2A). Furthermore, ENE trending strike-slip faults are also present, though they do not form a well-defined set but exhibit instead scattered E to NE trends (Figure 2A). Paleostress analysis reveals two distinct stress regimes: one characterized by WNW–ESE compression and another by NNE–SSW compression, associated with transpressive and transtensive conditions, respectively (Figures 2B and 2C).

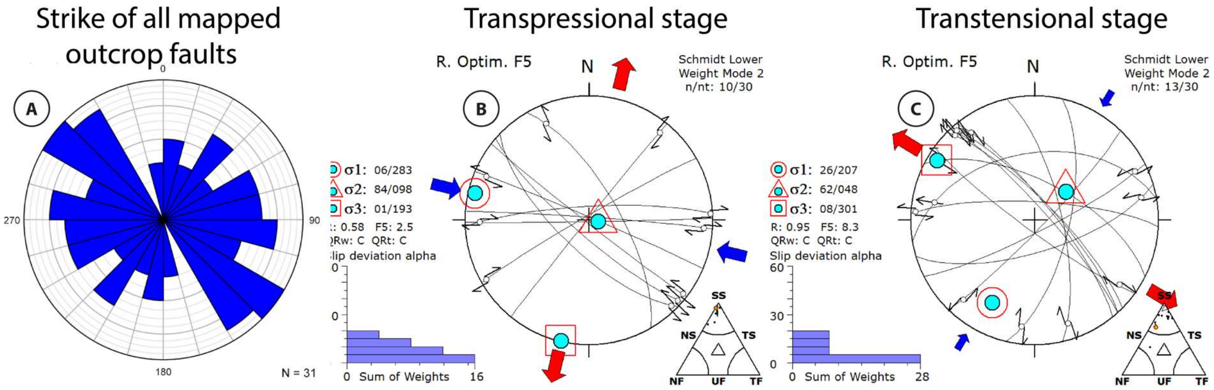

Figure 2. Fault orientation data and paleostress analysis results based on kinematic field observations. (**A**) Strike of mapped fault planes. Paleostress inversion with Wintensor software resulted in the identification of two separate faulting stages: (B) transpressional and (C) transtensional.

4. Relationship between faulting, mineral alteration, and crystalline reservoir formation

Our field and drone mapping revealed that many NW-trending strike-slip faults within the Vehmaa Batholith correlate with zones of pervasive mineral alteration (Figures 3 and 4). Typical mineral paragenesis within the alteration zones is chlorite, prehnite, and zeolite, indicating hydrothermal events of nearly 300 °C. Typically, the fractured and altered rocks within these zones display substantial porosity of ~10% and laboratory-measured permeabilities exceeding 2×10^{-15} m^2 under 50 MPa confining pressure. The strike-slip fault networks are hundreds-to-thousands of meters in total length and could form crystalline reservoirs with volumes exciding 1 km^3, which are promising targets for geothermal resources. Our findings particularly highlight that hydrothermal alteration linked to these faults can sustain high permeability even at depths >2 km, an observation consistent with the results of Bischoff et al. (2024).

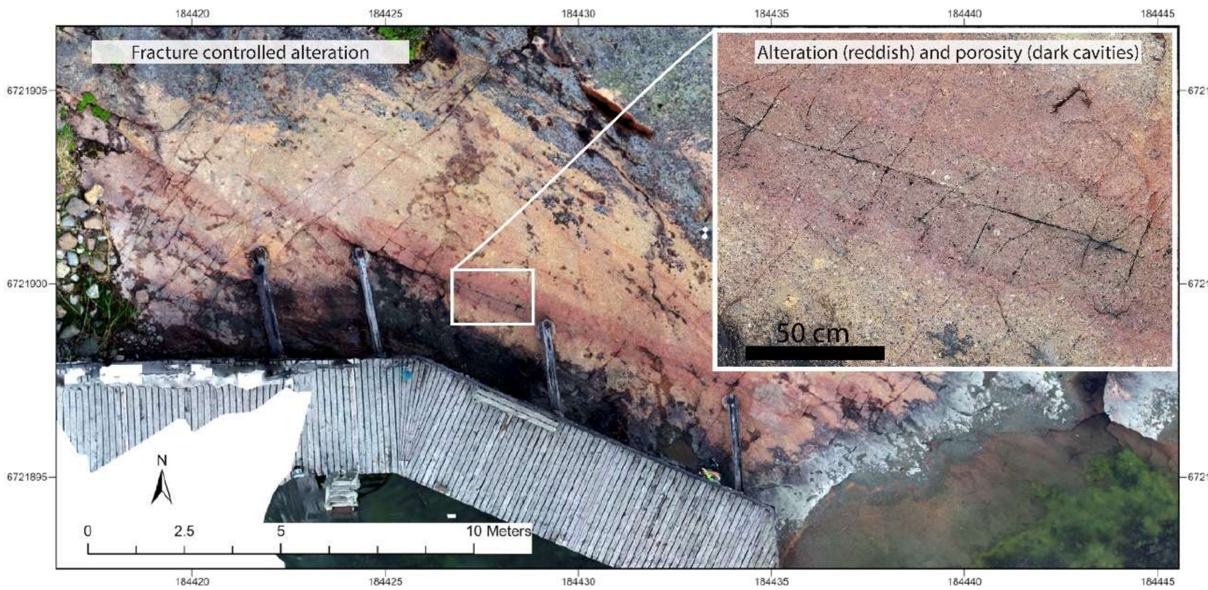

Figure 3. A drone orthomosaic image from an outcrop near Vuosnainen harbor, Kustavi, reveals fracture-controlled alteration (visible from dark reddish staining) and porosity (dark cavities) associated with NW–SE striking faults.

Figure 4. An outcrop-overview of a right-lateral strike-slip fault associated with zeolite, prehnite and chlorite alteration.

5. Conclusions

Our study of the Vehmaa rapakivi granite reveals that the batholith was affected by substantial, low-displacement strike-slip faulting and subsequent hydrothermal alteration. The most substantial alteration zones are mainly within NW–SE striking fault zones. The high-temperature (>200 °C) mineral assemblages infilling the strike-slip faults and fractures suggest Proterozoic hydrothermal processes. Results of the conducted paleostress analyses are compatible with those in the Åland rapakivi Batholith (Nordbäck et al., 2024), which further links to stress stages and faulting stages within the Olkiluoto site in Southwestern Finland (Nordbäck et al., 2022). These findings indicate that the majority of brittle post-rapakivi deformation occurred between 1.55 and 1.2 Ga (Nordbäck et al., 2024). By advancing our understanding of the brittle tectonic and thermal history that shaped the Fennoscandian crust during the Meso–Neoproterozoic, our study contributes to the identification of potential geothermal targets in southern Finland and other crystalline settings worldwide.

References:

Bischoff, AP., Heap, MJ., Mikkola, P., Kuva, L., Reuschlé, T., Jolis, Em., 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. https://doi.org/10.1016/j.geothermics.2023.102895

EMODnet Bathymetry Consortium, 2018. EMODnet Digital Bathymetry (DTM 2018). https://doi.org/10.12770/18FF0D48-B203-4A65-94A9-5FD8B0EC35F6

Hautaniemi, H., Kurimo, M., Multala, J., Leväniemi, H., Vironmäki, J., 2005. The “Three in One ” Aerogeophysical Concept of Gtk in 2004. Geological Survey of Finland, Special Paper 39, 21–74, 2005.

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

Nordbäck, N., Mattila, J., Zwingmann, H., Viola, G., 2022. Precambrian fault reactivation revealed by structural and K-Ar geochronological data from the spent nuclear fuel repository in Olkiluoto, southwestern Finland. Tectonophysics 824, 229208. https://doi.org/10.1016/j.tecto.2022.229208

Nordbäck, N., Skyttä, P., Engström, J., Ovaskainen, N., Mattila, J., Aaltonen, I., 2024. Mesoproterozoic Strike-Slip Faulting within the Åland Rapakivi Batholith, Southwestern Finland. Тектоніка 2, 1–26. https://doi.org/10.55575/tektonika2024.2.1.51