Title of the Research Plan

Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings

1 Aim and objectives

1.1 Significance of research project in relation to current knowledge, research based starting points:

Context and Scale

Discovering deep geothermal resources in crystalline rocks beyond high-temperature volcanic and rifting areas is pivotal to enable a rapid global transition towards clean and reliable energy sources. While high-temperature areas can promptly provide substantial geothermal resources, our limited understanding of the thermal and reservoir properties of deep crystalline rocks represents a roadblock for implementing new technologies in lower-temperature settings.

Our Deep-HEAT-Flows research project addresses this knowledge gap by identifying the fundamental thermogeological processes that create **large (>1 km³) and deep (>1 km) crystalline reservoirs in low-enthalpy (temperatures <150 °C) geothermal settings**, with a particular interest in the Fennoscandian Shield (Figure 1). The far-reaching impact of our research will be immediate, resolving exploration uncertainties of areas that have enormous geothermal potential but are currently considered commercially risky by the energy industry.

Finding Earth's heat is reasonably straightforward. As an empirical rule, the deeper you drill, the hotter it gets, making geothermal energy a nearly limitless natural resource still largely untapped (e.g. Arnórsson et al. 2015; Jolie et al. 2021). This rule also applies in lower-enthalpy crystalline settings, where the radiogenic decaying of minerals within *ancient* igneous and metamorphic rocks can add to impressive energy figures (Kukkonen 2000; Beckers et al. 2022). To illustrate, the crystalline bedrock beneath Finland is estimated to store nearly **4 000 000 TWh** of power at a depth interval of four to seven kilometres, **sufficient to supply the country's current district heating demands for over 100 000 years** (GTK 2022).

Whereas we can reach the Earth's "deep heat" with modern drilling technology, our capacity to harvest this power is limited by the rate that heat dissipates from its source, which is primarily a function of the fluid and thermal flow properties of rocks (Arnórsson et al. 2015; Duwiquet et al. 2021). Consequently, an accurate understanding of the parameters that control heat migration and storage, including porosity, permeability, pore connectivity, heat capacity, and thermal conductivity, is necessary to assess the potential of deep crystalline reservoirs and propose realistic geothermal exploration models.

Combining large-scale geophysical data, borehole and field information, and pore-scale microscopic observations, **Deep-HEAT-Flows will create novel conceptual models and tools to assess and reveal the processes that form optimal crystalline reservoir targets in low-enthalpy settings.** Our project will advance the state of the art to (i) understand the fundamental petrophysical properties of the deep crystalline crust and (ii) comprehend heat generation, transfer and storage at low-enthalpy conditions – essential information that will permit accurate forecasting for drilling and quantification of deep geothermal resources.

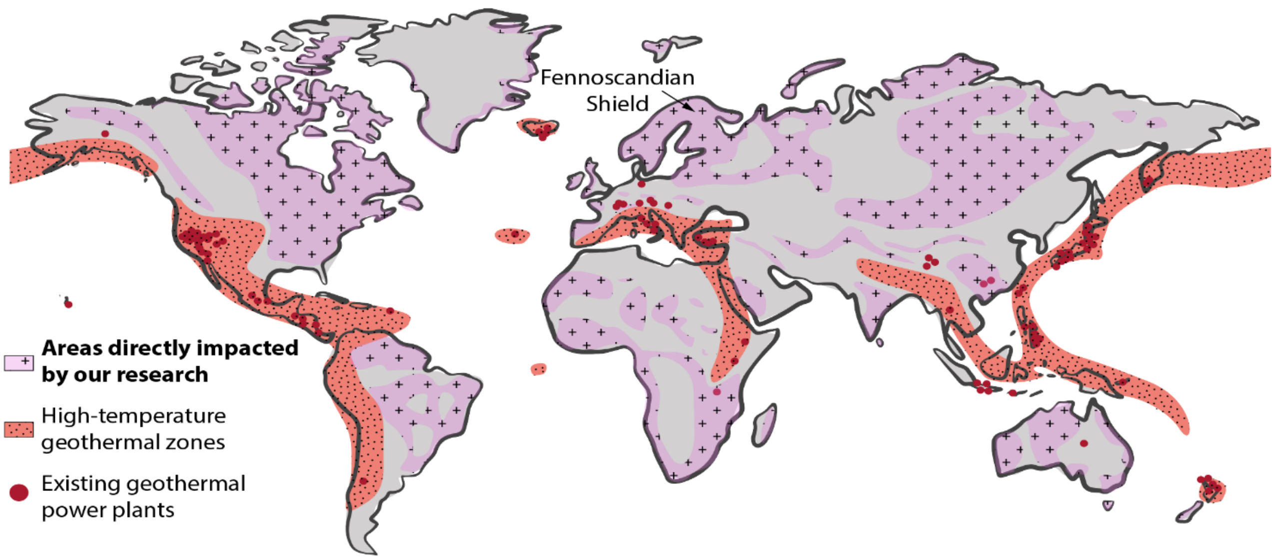

Figure 1: Simplified world geological-geothermal map highlighting the crystalline areas directly impacted by our research. Information compiled from the Global Atlas for Renewable Energy (www.irena.org/globalatlas) and the Geological Surveys Collaboration Programme (http://portal.onegeology.org/OnegeologyGlobal/).

Scientific and Technological Challenges

Large-scale (>1MW) geothermal production relies on two critical factors: heat and permeability (e.g. Kukkonen and Pentti 2021; Jolie et al. 2021). Presently, three (global) issues make the utilisation of deep geothermal heat in low-enthalpy crystalline settings challenging:

i. Substantial temperatures are achieved much deeper than in active volcanic or rifting areas (e.g. ca 100°C at 6 km in Finland; Kukkonen 2000);
ii. With progressive depths, large (>1 km^3) permeable structures become scarce and harder to detect based on our current exploration geophysics knowledge (Kukkonen 2011; Ranjram et al. 2015; Lecomte et al. 2015);
iii. The depth and low permeability combination lead to drilling and reservoir engineering complexity (Heap and Kennedy 2016; Villeneuve et al. 2018; Jolie et al. 2021).

Specifically in the Fennoscandian Shield, numerous permeable zones have been drilled in the uppermost 500 m of the crust (Kukkonen et al. 2011; Rosberg and Erlström 2021). At deeper levels, boreholes are rare (only ~10 have reached depths >1 km in Finland) and cannot represent the diversity of the deeper Fennoscandian crust. Where data is available, bacterial communities and saline brines indicate little groundwater movement, suggesting that permeability is too low or there is no hydro-or thermodynamic force driving deep fluid flow circulation (Purkamo et al. 2016). Where permeability was found at deeper levels, it was confined to narrow zones that could not support commercial geothermal production (Kukkonen 2011).

The frontier of geothermal production in deep crystalline settings is highlighted by recent obstacles to implement Enhanced Geothermal Systems (EGS), a novel technology designed to produce heat by creating artificial rock reservoirs. For example, the recent St1 Deep Heat Project in Southern Finland successfully created substantial hydraulic conductivity (~10^{-8} m/s) between two ~6 km deep boreholes, but permeability dropped significantly when the wellhead pressure was released (Kukkonen and Pentti 2021), and the project was deemed commercially unsuitable in 2022. Additional closed-loop Advanced Geothermal Systems (AGS) have been proposed as a solution for deep geothermal exploration. Still, the AGS technology relies exclusively on conductive heat flow, not allowing fluid circulation with its enclosing rocks, typically leading to low heat transfer coefficients unlikely to deliver long-term energy yields that justify the upfront investment of deep drilling (Piipponen et al. 2022; Beckers et al. 2022).

Permeability, the natural ability of rocks to transmit fluids, promotes **convective heat transfer**, enhancing the performance of geothermal reservoirs and the energy reward from boreholes (e.g. Wyering et al. 2014; Lamur et al. 2017; Jolie et al. 2021). Consequently, **increasing our scientific understanding of the thermogeological processes that create highly permeable crystalline reservoirs in deep, lower-enthalpy settings** is necessary to ensure that geothermal resources can become economically available globally.

New Science and Understanding

Unlocking the full potential of deep geothermal resources in crystalline settings beyond volcanic and rifting areas will require novel research and significant technological innovation. Much of our current knowledge concerning geothermal systems comes from *thermodynamically active areas* where (i) high-temperature fluids, (ii) intense tectonic and volcanic activity, and (iii) the presence of convective hydrothermal cells play a central role in forming geothermal reservoirs (Gudmundsson et al. 2000; Ledesert et al. 2009; Arnórsson et al. 2015; Bischoff et al. 2021).

It is broadly accepted that processes like rock fracturing and mineral alteration are key for defining the fluid flow properties of *higher-enthalpy* geothermal reservoirs (Wyering et al. 2014; Lamur et al. 2017; Duwiquet et al. 2021). Conversely, fundamental knowledge of how these processes are likely to affect the fluid flow properties of deep crystalline reservoirs at *lower-enthalpy conditions* is lacking. Therefore, new scientific research is necessary to understand variables such as:

i. The relationships between fracturing, faulting and mineral alteration;
ii. The thermal conductivity and geomechanical strength of fractured and altered rocks;
iii. The pore-space morphology and connectivity of complex crystalline reservoirs;
iv. The permeability ratio between stable crustal fault zones and their host rocks;
v. The size and geometry of fracture networks near and within ancient igneous intrusions;
vi. The ability of seismic reflection methods to detect discrete fracture networks.

Deep-HEAT-Flows will contribute to solving these challenging aspects of geothermal exploration, **expanding our capacity to find natural crystalline reservoirs while facilitating petrophysical and geomechanical information to improve EGS and AGS technology.** Ultimately, results from our research will permit the industry and regulatory agencies to access critical scientific knowledge about the deep crystalline crust, reducing drilling uncertainties and ensuring the success of new geothermal exploration endeavours - an essential step in laying the foundation for a sustainable, low-carbon, and resilient society.

1.2 Research questions and/or hypotheses:

Our research questions and hypothesis will adapt and advance the global horizons to explore deep geothermal resources in low-enthalpy settings. **We hypothesise that substantially large (>1 km^3) geological structures can host highly permeable crystalline reservoirs at depths > 1 km** (Figure 2). The most promising geological structures are *(i) crustal fault zones and (ii) the contact zone of ancient igneous intrusions* (Figure 3). Both structures occur in great numbers in the Fennoscandian Shield and as such have significant potential to provide drillable targets for deep geothermal exploration (e.g. Burchardt et al. 2011; Rosberg and Erlström 2021).

In both cases, novel research from active geothermal areas and our preliminary observations in the Fennoscandian Shield suggest that (i) these structures form connected fracture networks that can create pathways for deep groundwater circulation, which (ii) induce mineral alteration and dissolution, (iii) enlarging the fracture size and aperture, (iv) increasing pore-throat radius, (v) reducing fluid flow tortuosity, and (vi) expanding the reservoir volume – all critical factors that enhance the performance of geothermal reservoirs (e.g. Wyering et al. 2014; Ledesert et al. 2009; Heap and Kennedy 2016; Bischoff et al. 2021). Determining these variables (**particularly the effects of fracturing and mineral dissolution**) is still in its infancy and is critical in defining a new paradigm of crystalline reservoir formation in low-enthalpy settings (Figure 2).

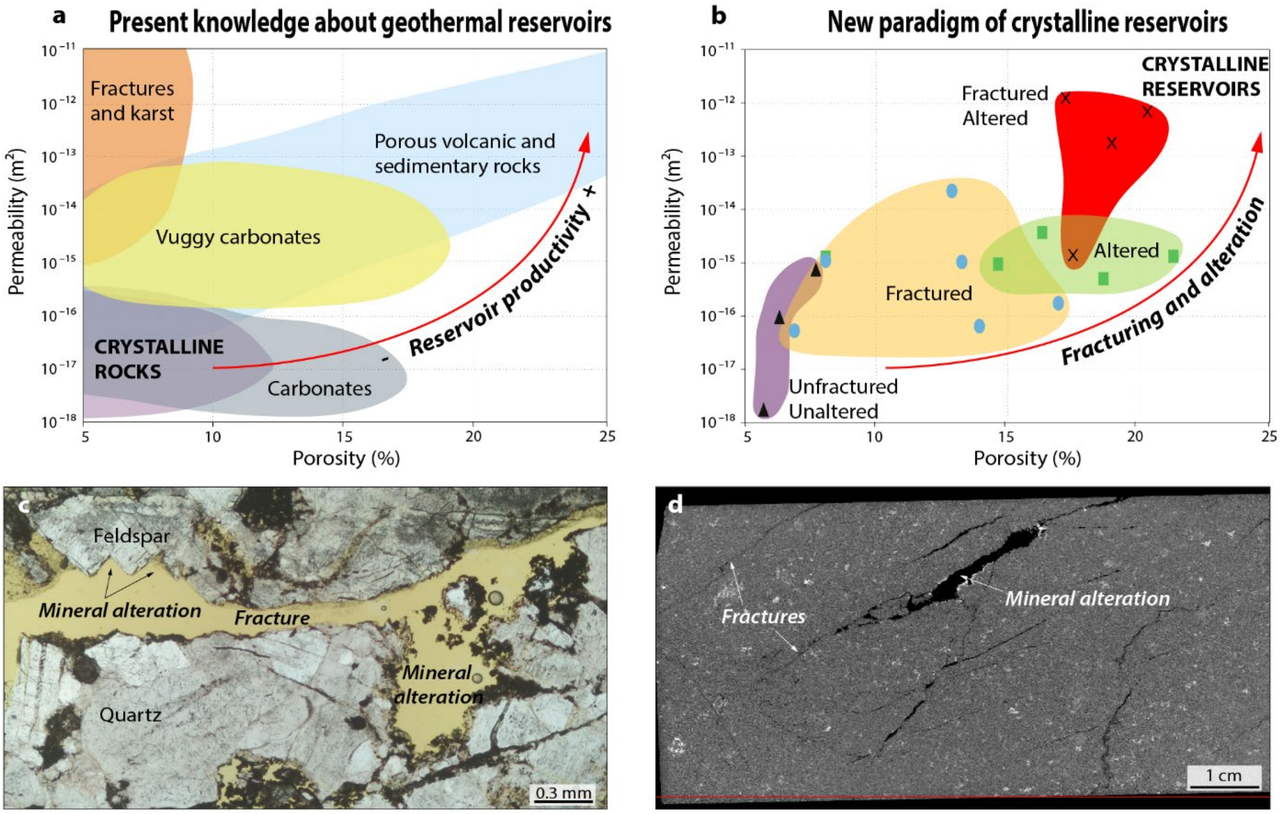

Figure 2: (a and b)Typical porosity and permeability plots of diverse rock types adapted from Jolie et al. (2021) and Duwiquet et al. (2021). (c) Thin-section and (d) computed tomography images showing fractures and dissolution pores (yellow) on a biotite granite sampled at 1351 m deep from the Koillismaa Deep Borehole, Eastern Finland.

Deep-HEAT-Flows will thus explore our hypothesis by answering three fundamental questions:

1- What are the critical thermogeological processes controlling parameters such as porosity, permeability and thermal conductivity of prolific deep crystalline reservoirs?
2- What are the optimal sizes, interconnectivity, and 3D morphologies of crystalline reservoirs related to stable crustal fault zones and ancient igneous intrusions?
3- How much and how fast can heat be extracted from these reservoirs?

1.3 Expected research results and their anticipated scientific impact, potential for scientific breakthroughs and for promoting scientific renewal:

Developing low-enthalpy geothermal resources in deep crystalline settings is a global challenge. Notably, these settings comprise vast parts of the Earth (Figure 1) that could immediately benefit from producing geothermal fluids for direct space heating, industrial purposes, and electricity generation by using binary cycle power plants (Jolie et al. 2021; Beckers et al. 2022).

The scientific stretch of our research will advance global knowledge in:

i. Multidisciplinary geoscience, integrating large-scale geophysical, field mapping and borehole observations with pore-scale analysis to delineate crystalline reservoirs;
ii. New fundamental petrophysical, thermal, and geomechanical data for geothermal exploration and modelling in crystalline areas;
iii. Advanced understanding of the processes that control crystalline reservoir formation, **particularly increasing knowledge about the relationship between fracturing and mineral alteration, for which only basic knowledge exists;**
iv. New conceptual models and tools to de-risk deep geothermal exploration while supporting EGS and AGS designing and implementation.

Additionally, Deep-HEAT-Flows will promote scientific renewal about the geothermal potential of the Fennoscandia crust by:

i. Demonstrating that highly permeable crystalline reservoirs exist at depths >500 m;
ii. Confirming that stable crustal fault zones and the contact zones of ancient igneous intrusions can form extensive interconnected fracture and mineral dissolution networks for deep circulation of hot geothermal fluids.

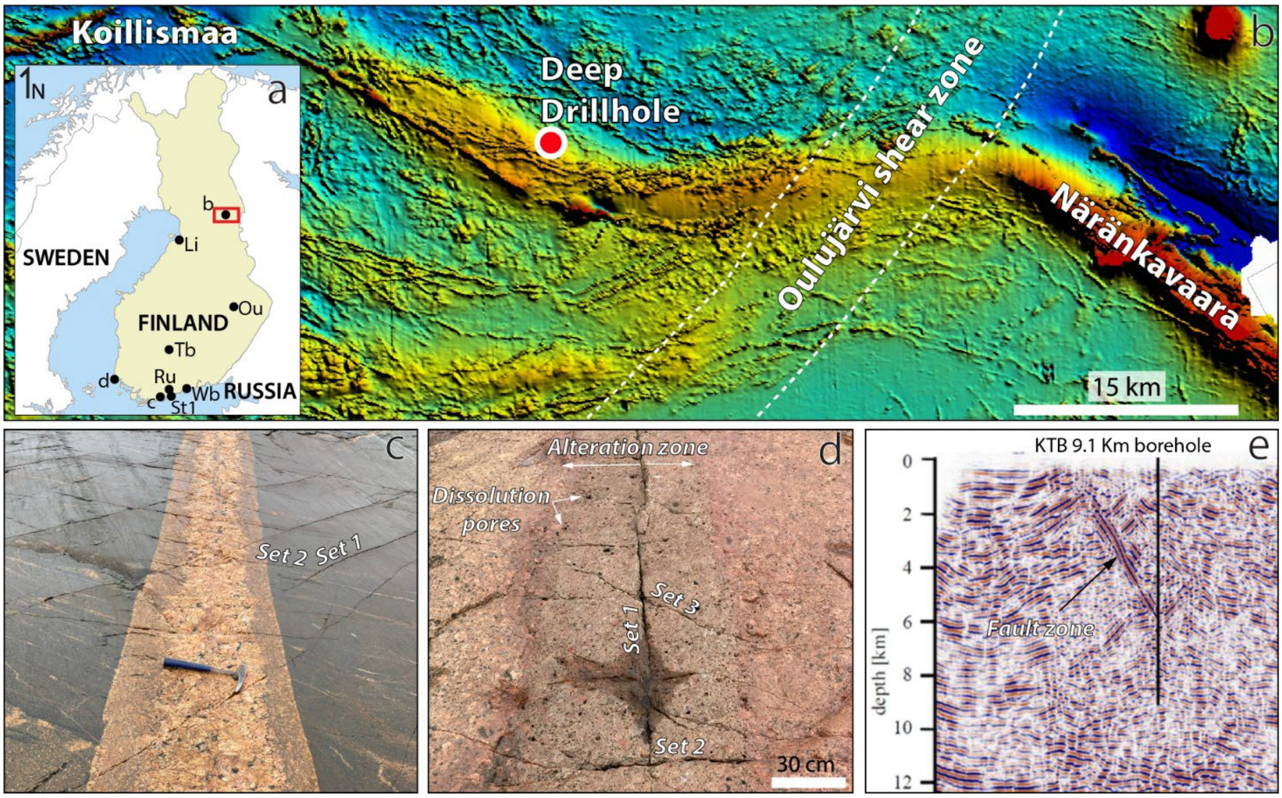

Figure 3: (a) Map showing the location of the boreholes Koillismaa (b) Liminka (Li), Outokumpu (Ou), Tampere (Tb), Ruskeasuo (Ru) and St1 Deep Heat (St1), and outcrops Vehma Pluton (d), Kopparnäs (c) and Wiborg Batholith (Wb) proposed in our study. (b) Aeromagnetic image of the Koillismaa area. (c) Orthogonal fractures in paragneisses and a pegmatitic vein, Kopparnäs Fault Zone. (d) Sets of fractures and dissolution pores in rapakivi granites, Vehma Pluton. (e) Seismic reflection image of a fault zone in crystalline setting, western Germany (Szalaiová et al. 2015).

By increasing our understanding of crystalline reservoirs and the petrophysical properties of the deeper crust, potential additional scientific breakthroughs include (i) finding reservoirs within mafic-ultramafic rocks that could serve for CO_2 sequestration purposes, (ii) screening for co-and by-products (e.g. lithium, rubidium, hydrogen, radon) likely to occur in low-enthalpy geothermal ventures, (iii) estimating the geomechanical behaviour of possible sites for underground hydrogen storage, and (iv) revealing evidence of the mechanisms that may trigger earthquakes during artificial enhancement and production of EGS enterprises. Consequently, the novelty of Deep-HEAT-Flows and its potential scientific breakthroughs will make geothermal energy more cost-effective, reducing geotechnical and environmental hazards uncertainties, and supporting our global climate-changing mitigation goals.

2 Implementation

2.1 Work plan and schedule:

Deep-HEAT-Flows research plan centres on three Work Packages (WP), described in detail below and complemented in section 2.2. Each WP addresses an essential element of geothermal exploration, respectively answering the three fundamental questions defined in session 1.2.

WP1: RESERVOIR PROSPECTIVITY determines the critical thermogeological processes controlling fluid and thermal flow properties of prolific crystalline reservoirs.
Task 1.1: Deep Crust Analysis collects samples and interprets wireline logs, images, and thermal data from key deep boreholes across Finland (e.g. Koillismaa, St1 Deep Heat, Ruskeasuo, Tampere, Liminka and Outokumpu), investigating crystalline reservoirs at depths up to 6 km.
Task 1.2: Outcrop Analogue collects geological information and samples from four outcrop locations (i.e. Vehma Pluton, Wiborg Batholith, Kopparnäs Fault Zone, Porkkala-Mäntsälä Shear Zone), assessing analogue rock types and structures suitable for deep geothermal exploration.
Task 1.3: Reservoir Delineation and Performance conducts a suite of laboratory-based experiments on ~100 samples from Tasks 1.1 and 1.2 to understand and quantify petrophysical, thermal, and geomechanical parameters of crystalline reservoirs and enclosing rocks. Measure the fluid flow properties of ~30 selected samples at progressive confining pressures, simulating the performance of target crystalline reservoirs at industry-relevant depths.
Task 1.4: Reservoir Formation performs microscopic, nanoscopic and 3D tomographic analysis on ~150 target samples from Tasks 1.1 and 1.2 to determine key mineral phases, alteration products and fracture networks of crystalline rocks. Quantify critical microscale (<10 cm) variables such as pore-space morphology and connectivity of crystalline reservoirs.

WP2: CRUSTAL STRUCTURE ARCHITECTURE sets the optimal sizes, geometries, and connectivity of crystalline reservoirs formed at stable fault zones and ancient igneous intrusions.
Task 2.1: Virtual Outcrops construct digital models of a minimum of two target locations from Task 1.2 to quantify the 2D mesoscale (cm to 100's m) interconnectivity of fracture networks within and around faults and igneous intrusions. Complement Tasks 1.3 and 1.4, assessing the relationships between fracturing and mineral alteration. Determine the permeability ratio between faults, intrusions, and their host rocks.
Task 2.2: Seismic Waveform Modelling create synthetic seismograms reproducing the geophysical characteristics of optimal locations selected from Tasks 1.1, 1.2 and 2.1, permitting the representation of sub-seismic scale rock property variations. The goal is to simulate diverse scenarios, testing to what extent seismic reflection techniques can capture details of the subsurface architecture of faults, igneous intrusions and associated crystalline reservoirs.
Task 2.3: Site-Specific Reservoir Architecture combines geological, geophysical, borehole, and field data to construct a 3D computational model that replicates the macroscale (>100's m) structural and stratigraphic framework of Koillismaa intrusions, faults and associated reservoirs. Define the sizes, geometries and interconnectivity of Koillismaa's crystalline reservoirs.

<u>WP3: RESERVOIR DYNAMICS</u> integrates the knowledge from WP1 and 2 to calculate crystalline reservoir volumes and delineate the energy yield from deep boreholes in low-enthalpy settings.
<u>Task 3.1:</u> <u>Finite Element Geothermal Simulation</u> develops surrogate models to estimate the performance of deep crystalline reservoirs under variable geological and engineering conditions. Models will simulate the injection and production of geothermal fluids at hypothetical sites over decadal time scales.
<u>Task 3.2:</u> <u>Prospective Models</u> integrate the results from the above to construct novel conceptual exploration models indicating the optimal geological processes, sizes, geometries, depths, and expected energy yields from low-enthalpy crystalline reservoirs.

		Year 1				Year 2				Year 3				Year 4			
	quarters	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
WP1- RESERVOIR PROSPECTIVITY																	
Task 1.1	Deep Crust Analysis	■	■	■	■	■											
Task 1.2	Outcrop Analogues			■	■	■											
Task 1.3	Reservoir Delineation and Performance					■	■	■									
Task 1.4	Reservoir Formation						■	■	■	■							
WP2: CRUSTAL STRUCTURE ARCHITECTURE																	
Task 2.1	Virtual Outcrops								■	■	■						
Task 2.2	Seismic Waveform Modelling									■	■	■					
Task 2.3	Site-Specific Reservoir Architecture											■	■	■			
WP3: RESERVOIR DYNAMICS																	
Task 3.1	Finite Element Geothermal Simulation												■	■	■		
Task 3.2	Prospective Models															■	■

Figure 4: Gantt chart explaining the timeframe of our research project.

2.2 Research data and material, methods, and research environment:

Our approach is multidisciplinary, combining insights from petrography, geochemistry, structural geology, igneous systems, petrophysics, rock mechanics and geophysics into a unified model that explains low-enthalpy crystalline reservoirs. Resources required for this project, including computer workstations and software, laboratory facilities, and equipment, are presently available at the Geological Survey of Finland (GTK) or through collaborator's institutions. All critical raw geophysical and borehole data are part of GTK's digital databank or are located at GTK's National Drill Core Archive. Outcrop areas for field data acquisition (Tasks 1.2 and 2.1) have been checked and are suitable for the proposed studies (Figure 3).

<u>Deep Crust Analysis</u> describes drillcore lithologies and interprets wireline logs to assess in-situ petrophysical parameters (e.g. density, resistivity, magnetic susceptibility) of deep crystalline reservoirs. Structural parameters, including fracture density, aperture, and orientation, will be defined by Optical and Acoustic Borehole Imaging interpretation. Data from Distributed Temperature Sensing will provide 1D thermal constraints.
<u>Outcrop Analogue</u> acquire detailed field information defining textures, structures, compositions, alteration degrees, geometries, sizes, and contact relationships of various crystalline rock bodies and reservoirs. Collects samples for tests planned in further tasks.
<u>Reservoir Delineation and Performance</u> perform standard laboratory tests to quantify the petrophysical (connected porosity, permeability, density, seismic waves velocities), thermal (heat capacity, thermal conductivity), and geomechanical (rock mass strength, elastic modulus) parameters of massive, fractured and altered rock targets from Tasks 1.1 and 1.2. Develop new methods to assess how these parameters vary due to rock fracturing and mineral alteration.

Reservoir Formation combines well-established petrographic techniques (i.e. thin-sections description) with cutting-edge analytical methods (i.e. 3D Computed Tomography scanning, Micro X-ray Fluorescence spectrometry, Scanning Electron Microscopy, and Electron Microprobe analysis) to assess the geochemistry and pore network of rock targets from Tasks 1.1 and 1.2.
Virtual Outcrops integrates field description with drone photogrammetry to provide high-resolution 2D digital maps (pixel size ~0.55 cm) of fracture and fault networks. A semi-automated topological analysis will be performed using TopoScan software to quantify fracture attributes, including aperture, connectivity and spatial organisation. Information from Tasks 1.3 and 1.4 will provide constraints to assess the fracture and mineral dissolution relationships.
Seismic Waveform Modelling combines geometric information from fault and fracture networks (Tasks 1.2 and 2.1) with the elastic rock properties from wireline logs (Task 1.1) and core samples (Task 1.3), simulating the seismic response of various geological units, structures and reservoirs at diverse scales. Point-spread function convolutional modelling algorithm from NORSAR SeisRoX software will be used for fast and low-cost simulation of pre-stack depth migrated seismic data, considering variable signal frequencies and angular illumination.
Site-Specific Reservoir Architecture uses Leapfrog software to interpret and compile existing geophysical data (i.e. seismic reflection, magnetic-gravimetric, and magnetotelluric surveys) with new borehole and field information from Tasks 1.1 and 1.2 into a 3D geological-structural model of the Koillismaa area. Generate a Digital Fracture Network using FracMan software or similar to define the geometry and interconnectivity of faults and fractures. Uses a Play Fairway Analysis approach to highlight the best drilling targets for deep geothermal boreholes. Where geophysical imaging lacks the resolution to resolve reservoir and structural architecture, results from Tasks 2.1 and information from the literature will guide our interpretations.
Finite Element Geothermal Simulation uses COMSOL Multiphysics software to build hypothetical models under varying reservoir (e.g. geometries, porosity and permeability) and engineering (extraction-production rates) parameters, forecasting the energy outcome from boreholes and estimating geothermal resource sizes. Uses stochastic and sensitivity analysis to investigate alternative reservoir scenarios.
Prospective Models compile information from the literature with our data from previous tasks to assess the fundamental elements of low-enthalpy geothermal systems (e.g. heat source, reservoirs, cap rocks, fracture networks). Interact these elements to build 2D cross-sections that illustrate the most promising conceptual scenarios for deep geothermal exploration in low-enthalpy crystalline settings.

2.3 Risk assessment and alternative implementation strategies:

The primary risk preventing the successful implementation of Deep-HEAT-Flows results is that crystalline rocks may not deliver substantial hydraulic conductivity to support large-scale heat production. Where local results may show low geothermal potential, we will investigate whether global situations resemble the local case-study conditions and delineate the more challenging requirements necessary for further assessment of these resources. Technical risks and mitigations relevant to the project are detailed in Table 1.

Table 1: Potential risks and mitigation strategy adopted to ensure our project's results and broad outreach impact.

Potential Risks	Mitigation Strategy
Missing legacy drillcore, maps or geophysical data.	Interface with international Geological Surveys, extended networks, or geothermal industries to secure access from other sources if our records are missing.
Timely access to critical computer hardware and software.	All the necessary computer software and hardware are ready for project commencement. Each entity involved in the project has sufficient additional resources available in this area to cover any shortfall.

Missing or uncertain inputs to numerical models.	Use values from similar studies published in the literature. Perform sensitivity tests with these parameters to mitigate variability in the model outcomes.
Limited team communication and collaboration.	Given the wide range of expertise of the research team, good communication will be essential. We will promote fortnightly meetings between researchers, the broader team, collaborators and GTK's research managing experts.
Permission declined to collect samples in critical areas, or too few petrophysical measurements to characterise the crystalline reservoirs target sites.	GTK holds permits that will be extended to the present research. If permitting issues arise, samples will be selected in areas outside sensitive boundaries and/or areas not subjected to regulations. In addition, GTK's massive National Drill Core Archive accounts for ~3,5 million metres of drill cores immediately available for use.
COVID-related lockdown or Russia-Ukraine conflict spill across international borders impacting access to laboratories. Equipment breakage for laboratory testing.	Our research organisations have developed a remote access network for computers and software. Interface with the research organisations to dispatch permits for critical access to laboratories that need physical maintenance and tests. Our global partner institutions have overlapping equipment to backed-up experiments.
Not able to recruit a suitable post-doctoral researcher.	We will immediately contact our extensive international network and advertise a desirable full-time four-year position to attract a suitable researcher. If a Postdoc is not available, we will recruit a research assistant and a PhD student.

3 Applicant, possible research team and collaborators

Our multidisciplinary team combines globally recognised researchers with EU's next-generation leaders and early-career talents. Collectively, our team has nearly 250 years of industry and academic experience, including conducting large scientific programmes. At the team's core are expert geothermal, geomechanical, geophysical, geomodellers, and structural geologists with international recognition for outstanding science excellence. Self-funded expert advisors will reinforce the team's quality and capacity to produce impactful scientific research (Table 2), further supported by an extended international academic and industry collaboration network. The Letters of Collaboration document provides details about our partners and their role in the project. Critical to our project's success is recruiting a highly-qualified and motivated post-doctoral researcher with exceptional petrophysical, geophysical, and heat flow modelling skills.

Table 2: Research team and collaborators. GTK (Geological Survey of Finland).

Team member	Country	Role	Expertise
Dr Alan Bischoff	Finland (GTK)	Principal Investigator	Multiscale geothermal reservoir characterisation
Unnamed postdoc (PD1)	Finland (GTK)	Key Researcher	Petrophysics, geophysics, modelling
Prof Alan Butcher	Finland (GTK)	Key Researcher WP1	Analytical methods and geochemistry
Dr Jukka Kuva	Finland (GTK)	Key Researcher WP1	Core-scale 3D tomography
Dr Michal Malinowski	Finland (GTK)	Key Researcher WP2	Geophysics and borehole analysis
MSc Kaiu Piipponen	Finland (GTK)	Key Researcher WP3	Finite element modelling
MSc Jon Engström	Finland (GTK)	Key Researcher WP2	Structural geology and drone photogrammetry
Dr Teppo Arola	Finland (GTK)	Expert advisor WP1	Geothermal exploration and industry network
Prof Pietari Skyttä	Finland	Expert advisor WP2	Structural geology and crustal processes
Assoc Prof Marlene Villeneuve	Austria	Expert advisor WP1	Geomechanics and drilling operations
Prof Michael Heap	France	Expert advisor WP1	Petrophysics and crystalline reservoirs
Assoc Prof Steffi Burchardt	Sweden	Expert advisor WP2	Structural geology and igneous systems
Prof Andy Nicol	New Zealand	Expert advisor WP2	Structural geology and seismic analysis
Prof Ilmo Kukkonen	Finland	Expert advisor WP3	Thermal modelling and geothermal systems
Dr David Dempsey	New Zealand	Expert advisor WP3	Geothermal modelling and engineering
Dr Ludmila Adam	New Zealand	Expert advisor WP3	Numerical modelling and rock physics
Dr Christopher Rochelle	UK	Expert advisor WP1	Geochemistry and rock-fluid interactions
Assoc Prof Luana Florisbal	Brazil	Expert advisor WP1	Geotectonics and igneous systems
Prof Sverre Planke	Norway	Expert advisor WP2	Seismic analysis of igneous rocks and structures

3.1 Project personnel and their project relevant key merits:

Our core team have been effectively collaborating for nearly a decade. Members of our research team (Nicol, Adam, Dempsey, Villeneuve, Bischoff) recently secured ~€10M in funds to assess the feasibility of storing hydrogen in natural rock reservoirs, which will add perspectives and complement our Deep-HEAT-Flows research goals.

The **Principal Investigator,** Dr Alan Bischoff, is a mid-career researcher (stage 3) with international industry and academic experience co-leading multidisciplinary scientific research programmes. His geological background spans several disciplines characterising crystalline reservoirs, stratigraphy, volcanology, igneous systems, tectonics and geophysics. Dr Bischoff currently holds a geothermal scientist position with the Energy and Construction Solutions Unit (Geoenergy Team) at the GTK, developing scientific and commercial projects designed to increase geothermal energy uptake in Nordic countries and globally. Previous expertise includes five years working as a petroleum exploration geologist offshore Brazil, gold mining exploration in New Zealand, and over seven years studying igneous reservoirs as an academic researcher at the University of Canterbury, where he concluded his PhD in 2019. PI's research merits are detailed in the "merits and increased competencies" section.

The **WP1 Reservoir Prospectivity** team (Bischoff, PD1, Kuva, Butcher, Heap, Villeneuve, Rochelle, Florisbal) has extensive experience characterising the reservoirs properties of crystalline and sedimentary rocks using information from drillholes, outcrops, petrophysical, geomechanical, and analytical data – all critical parameters to delineate the potential of geothermal reservoirs. The **WP2 Crustal Structure Architecture** team (Bischoff, PD1, Engström, Malinowski, Burchardt, Nicol, Skyttä, Planke) includes experts in geophysical and structural geology, particularly characterising the geometry of crustal faults and igneous intrusions and their relationship with fluid flow properties of crystalline rocks and geothermal reservoirs. The **WP3 Reservoir Dynamics** team (Bischoff, PD1, Piipponen, Kukkonen, Adam, Dempsey) have experience in multiscale fluid-flow and thermal modelling of porous and crystalline reservoirs, with applications to geothermal, CO_2 sequestration, and groundwater resource delineation. In addition, the team has extensive knowledge of multiphysics modelling using finite element methods, stochastic analysis, and computational simulations to resolve complex structural assessment, heat transfer, fluid flow, and mass transport calculations.

3.2 Collaborators:

Building networks and national/international collaboration are central to the Deep-HEAT-Flows project. We will leverage the PI's extensive network developed over a decade of research and industry experience in New Zealand, Australia and Brazil with new partnerships in the EU to generate capacity building and share critical knowledge/infrastructure/laboratory for assessing geothermal resources. In addition, Deep-HEAT-Flows will open opportunities for developing a pioneering 'Renewable Geoenergy Hub' designed to increase our scientific understanding of low-enthalpy geothermal resources in deep crystalline settings – key to discover the next generation of deep geothermal resources and achieve global decarbonisation targets.

4 Responsible science

4.1 Research ethics, equality and nondiscrimination, open science, and sustainable development:

Following the ethical standards, directives and guidelines of the European Code of Conduct for Research Integrity (https://allea.org/code-of-conduct/), the Finnish National Board of Research Integrity (https://tenk.fi/en), and GTK's core values (https://www.gtk.fi/en/strategy-2020-2023-2/values/), our Deep-HEAT-Flows research will prioritise impartiality, independence, reliability and integrity, ensuring the quality and trustworthiness of our results. Honouring the GTK's code of conduct guidelines (www.gtk.fi/wp-content/uploads/2020/05/Codeofconduct_2020.pdf) and the Finnish Non-Discrimination Act 21/2004 (www.finlex.fi/fi/laki/kaannokset/2004) we will prevent all discrimination based on gender, age, origin, nationality, language, religion, belief, opinion, political activity, trade union activity, family relationships, state of health, disability, sexual orientation, or other personal characteristics.

In line with GTK's and FAIR (www.go-fair.org/) data policy, all new data, tools and knowledge developed within this project will be distributed to the public domain free of charge as part of the Finnish National Repository of Geological Information (www.gtk.fi/en/services/data-sets-and-online-services-geo-fi/national-geological-database/). Scientific results will be disseminated via open-access publications in high-impact, international peer-reviewed scientific journals, conference presentations, and workshops. Where data or knowledge generated by this programme is proprietary to our partners, we will seek agreement to publish key findings as part of an open-access strategy. In addition, we will use GTK's website and social media (e.g. LinkedIn; ResearchGate) to publish regular updates on the project. At the end of the project, all results (Terabytes of data) will be made available as open-access information in https://hakku.gtk.fi/en, through a Creative Commons licence. **We anticipate that our results will produce a minimum of eight publications in top journals on the topic in question** (e.g. Nature Energy, Renewable Energy). Notably, our project will help accelerate the transition to a sustainable, carbon-neutral society and economy, supporting the United Nations Sustainable Development Goals #7, #8, #9, #11 and #13 (https://sdgs.un.org/).

5 Societal effects and impact

5.1 Effects and impact beyond academia:

Deep-HEAT-Flows will acquire new data and deliver scientific knowledge demonstrating the technical feasibility of producing geothermal energy from deep and low-enthalpy crystalline reservoirs. Industry and regulatory agencies will have access to this critical knowledge necessary to perform new resource delineation, new policies, and new drilling parameters for geothermal exploration. This new scientific knowledge will guide the implementation of pilot projects, initially targeting strategic areas to demonstrate the feasibility of small-scale developments and further enabling low-enthalpy geothermal resources to become predictable at industrial scales. Collectively, Deep-HEAT-Flows results and pilot projects will further mitigate future drilling risks and assist the design and implementation of EGS and AGS systems. To ensure the uptake of our research, we will organize two seminars for stakeholders, dedicated to both policymakers and industry during the 3rd and 4th years of the project.

In a five-year post-research horizon, government incentives and stakeholders will create numerous opportunities for new geothermal energy enterprises, initially for district heating and further for electricity generation as technology advances. Making low-enthalpy geothermal resources commercially available will ensure a steep change in our global strategic energy security, maximising reliable renewable sources while supporting our decarbonisation goals. Additional societal effects include developing 'green technology hubs', catalysing partnerships between Finnish and international institutions, and creating high-value expertise, jobs, and intellectual property. Finally, decarbonising our energy systems will disrupt communities and industries. Aligned with the Just Transition framework (https://climatejusticealliance.org), **the uptake of our project will encourage skilled people and existing fossil fuel-dependent regions to join the transition towards a greener economy.**

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Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings

LETTERS OF COLLABORATION

This document presents a compilation of the Letters of Collaboration stating the genuine and long-term commitment critical to the implementation of our Deep-HEAT-Flows project. All collaborators stressed the urgent need for clean and sustainable energy sources that can meet large-scale commercial applications and support global decarbonisation goals. In addition, all research collaborators state that moving beyond hot volcanic and rifting areas is critical for achieving the full expansion of the geothermal energy industry globally. Furthermore, collaborators agreed that the straightforward path to achieve the global impact of our research is to increase the uptake of geothermal resources in lower-enthalpy crystalline areas. Thus, it is common sense among our team that our novel scientific research is necessary to resolve critical knowledge gaps to find these lower-enthalpy resources, particularly increasing our understanding of the fluid and thermal properties of crystalline rocks that form prolific deep geothermal reservoirs. In particular, Prof. Andy Nicol (PI's PhD supervisor) addressed the PI's distinguished potential as an innovative researcher capable to lead multidisciplinary groups and produce impactful geothermal research. The following table summarises our collaborator's main aims and roles.

Collaborator	Country and Organisation	Description
Prof Pietari Skyttä	Finland, University of Turku	Support acquisition and analysis of structural data in the Fennoscandian Shield (Task 1.2, including expert advice in drone photogrammetric analysis (Task 2.1). Open teaching opportunities at the University of Turku
Assoc Prof Marlene Villeneuve	Austria, University of Leoben	Provide expert advice regarding rock mechanical analysis of crystalline rock masses (Task 1.3). Attend workshops and fieldwork in support of the development and dissemination of the project results
Prof Michael Heap	France, University of Strasbourg	Provide training and access to the laboratory equipment at ITES that can measure the physical, mechanical, and heat transport properties of rocks (Task 1.3)
Assoc Prof Steffi Burchardt	Sweden, University of Uppsala	Offer expert advice interpreting complex brittle structures in the Fennoscandian crust (Task 1.2)
Prof Andy Nicol	New Zealand, University of Canterbury	Collaborate to develop models describing the geometry and interconnectivity of crustal fault zones and damaged zones in igneous intrusions (Task 3.3). Conceptualise and write scientific papers
Prof Ilmo Kukkonen	Finland, University of Helsinki	Guide data acquisition and geothermal modelling in the Fennoscandian Shield (Tasks 1.1 and 3.2)
Dr David Dempsey	New Zealand, University of Canterbury	Provide training on computer modelling simulators developed especially for crystalline geothermal settings (Task 3.2)
Dr Ludmila Adam	New Zealand, University of Auckland	Provide advice on geophysical data analysis and numerical modelling of crystalline rocks (Task 3.3)
Dr Christopher Rochelle	UK, British Geological Survey	Offer expert advice in geochemistry and rock-fluid interactions (Task 1.3 and 1.4)
Assoc Prof Luana Florisbal	Brazil, Federal University of Santa Catarina	Plan and develop outreach educational activities targeting geology students and the wider community
Prof Sverre Planke	Norway, University of Oslo	Provide expert advice on seismic reflection interpretation and construction of synthetic seismograms (Task 2.2)

THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

SCIENCE
SCHOOL OF ENVIRONMENT

Ludmila Adam, Senior Lecturer

Science Centre
23 Symonds Street. Auckland,
New Zealand
T +64 9 9236458
Email: l.adam@auckland.ac.nz
The University of Auckland
Private Bag 92019
Auckland 1142 New Zealand

Dear Academy of Finland Assessors,

With this letter, I would like to support the project titled " Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings" submitted by Dr. Alan Bischoff. Although New Zealand is gifted with high-enthalpy geothermal resources, most are concentrated in the Taupo Volcanic Zone (TVZ), Central North Island. Making low-enthalpy resources available in locations away from the TVZ will ensure national energy security as New Zealand transit towards a zero-carbon economy. Furthermore, crystalline settings have an enormous unexplored potential yet to be discovered globally. Therefore, the research project proposed by Dr. Bischoff is aligned with the interests of my research group (Physics of Rocks Lab – PORO lab) and our university much welcomes this collaboration.

If this project is funded, my contributions will focus on the petrophysical, geophysical and numerical modelling aspects of the work. The PORO Lab will support Dr. Bischoff as follows:

- Provide access to University of Auckland laboratories for petrophysical and geophysical properties.
- Provide access to high-performance computing and data analytics facilities, such as the New Zealand eScience Infrastructure (NeSI), for researchers or students working with the PORO Lab.
- Advice on geophysical data analysis and numerical modelling.
- Share data from New Zealand geothermal reservoirs and modelling workflows
- Participate in workshops and other activities designed for sharing knowledge about this project
- Advice and help develop outreach educational activities targeting under- and post-graduated geology students and the wider community.
- Create opportunities for future research.

Sincerely,

Ludmila Adam

UPPSALA UNIVERSITET

To: The Academy of Finland

Uppsala 23rd June 2022

Steffi Burchardt

Associate Professor in Structural Geology

Department of Earth Sciences

75236 Uppsala

Visiting address:
Villavägen 16

Telefon/Phone:
+46 18 471 2568

www.steffiburchardt.com

steffi.burchardt@geo.uu.se

Object: Intent of Dr. Steffi Burchardt, Uppsala University, Sweden to contribute to the AKA Fellow application "Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings"

I am writing this letter to state my commitment and that of Uppsala University to contribute to the project "**Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings**" being submitted by Dr. Alan Bischoff. The exploration of geothermal resources in crystalline rocks has the potential to contribute to a solution of humanity's demand for energy, without negative consequences for the climate. The outcome of this project is of particular relevance to Sweden and Finland, as both countries share the same bedrock and geothermal conditions.

If the proposal submitted by Dr. Bischoff is selected for funding, it is my intent to collaborate as detailed in the Project Description by providing expertise to the project and share research outcomes. Specifically, I will

- support the acquisition and analysis of bedrock structures in Southern Finland outcrops (e.g. Vehma Pluton and Kopparnäs Fault Zone)
- offer expert advice interpreting complex brittle structures in the Fennoscandian crust
- provide access to up-to-date laboratory facilities, including the 3D Geology lab at Uppsala University
- share crystalline rocks data
- co-supervise, advise and assess MSc and PhD students within the framework of the project
- participate in workshops and other activities designed for sharing knowledge about this project

Sincerely,

Steffi Burchardt
Associate professor in Structural Geology, Uppsala University

Civil and Natural Resources Engineering
Pūhanga Metarahi me te Rawa Taiao
Tel: +64 364 2250, Fax: +64 3 364 2758
www.canterbury.ac.nz/civil

David Dempsey, Ph.D.
Senior Lecturer
Department of Civil and Natural Resources Engineering
University of Canterbury
4800 Private Bag, Christchurch - 8140, New Zealand

27 June 2022

To whom it may concern:

I am a Senior Lecturer in Civil and Natural Resources Engineering at the University of Canterbury in New Zealand. My research addresses numerical modelling of crystalline geothermal reservoirs, including thermodynamic performance, induced seismicity, well stimulation, economics, and optimization.

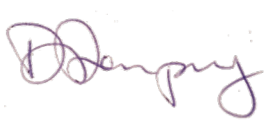
I would be pleased to formally collaborate with Dr Bischoff on his "Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings" research into crystalline geothermal resources. These resources are of increasing interest in New Zealand where our world-leading geothermal industry are looking to extend operations into deep crystalline rocks.

The purpose of this collaboration would be for me to assist Dr Bischoff in the numerical modelling requirements of his project. This includes:

1. Training on bespoke research simulators (FEHM, PyFEHM) that have been developed especially for crystalline geothermal settings.
2. Engagement with the wider scientific community on thermo-hydro-mechanical modelling of crystalline rock reservoirs.
3. Quality checking, debugging, and validation of the developed models.

Initial engagement with Dr Bischoff can occur remotely, as it is primarily involves setting up the computer modelling environment. All simulators are open-source and have training documents. Research visits will be coordinated around Northern Hemisphere conference travel.

Sincerely,



David Dempsey

To: The Academy of Finland

Florinaópolis 01st August 2022

UNIVERSIDADE FEDERAL DE SANTA CATARINA

Luana Moreira Florisbal

Associate Professor in Geological Mapping

Department of Geology

Campus Florianópolis

Visiting address:
R. Eng. Agronômico Andrei Cristian Ferreira, 240-432 -Carvoeira, Florianópolis – SC
BRASIL

Telefon/Phone:
+55 48 991759101

luana.florisbal@ufsc.br

I am writing this letter to state my and the Federal University of Santa Catarina commitment to contribute to the project **"Deep-HEAT-Flows: Discovering deep geothermal resources in crystalline rocks"** being submitted by Dr. Alan Bischoff. The increasing energy demands and related climate changing issues have put enormous pressure on the geoscientific community to find affordable, reliable, and rapid solutions for decarbonising our society and economy. Developing global multidisciplinary cooperation is key for catalysing innovative thinking and critical mass to discover the next generation of resources that will supply the world's energy demands while reducing environmental impacts. Geosciences have a central role in our energy transition, and I am enthusiastic about the possibilities that crystalline rocks have to offer for the geothermal industry. The outcome of this project is of particular relevance to Brazil, as the country is currently searching for geothermal resources in similar geological conditions to offset the reduction of our hydroelectric plants' capacity – perhaps another adverse effect of climate change. In addition, our University and under- and graduate students will enormously benefit from this partnership by creating networks and capacity building for the new generation of geoscientists to join the transition towards a renewable energy economy. If the proposal submitted by Dr. Bischoff is funded, I will collaborate as detailed in the Research Plan by providing expertise to the project and sharing research outcomes.

Specifically, I will:

- Support the acquisition and interpretation of crystalline rock types, crustal structures (faults and contacts of igneous intrusions) and their associated reservoirs
- Provide access to UFSC laboratories, including the petrophysical and modelling facilities.
- Share data about the South American crystalline basement and combine information from the Fennoscandia Shield to understand crystalline reservoirs globally
- Participate in workshops and other activities designed for sharing knowledge about this project
- Plan and develop outreach educational activities targeting under- and graduated geology students and the wider community

Sincerely,

Luana Moreira Florisbal
Associate professor in Geological Mapping, Federal University of Santa Catarina

Institut Terre & Environnement de Strasbourg | ITES | UMR 7063
de l'Université de Strasbourg & CNRS & ENGEES

05 July 2022

Letter of Collaboration for "Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings" by Dr. Alan Bischoff

To whom it may concern,

I hereby wish to express my support for the proposal by Dr. Alan Bischoff entitled "Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings".

I am a professor at the Institut Terre & Environnement de Strasbourg (ITES) at the University of Strasbourg in France. I am one of three members of permanent staff that work in the rock deformation laboratory at ITES. Our laboratory houses a wealth of purpose-built equipment designed to investigate the physical, mechanical, and transport properties of rocks. I am currently involved in several projects on geothermal energy exploitation in granitic reservoirs within the Upper Rhine Graben and French Massif Central, and so the project proposed by Dr. Alan Bischoff is not only in line with my research interests and goals, but also with those of the ITES. I would be delighted to contribute my expertise to this project and provide access to our laboratories at the ITES.

If the project is funded, I will support the project in the following ways:

- Provide expert advice related to the physical, mechanical, and transport properties of rocks.
- Share our understanding of the granitic geothermal reservoirs located within the Upper Rhine Graben and French Massif Central.
- Provide access to the laboratory equipment at ITES that can measure the physical, mechanical, and transport properties of rocks.
- Help integrate microscopic observations and laboratory measurements on rock samples with large-scale geophysical and field mapping datasets. Attend workshops and fieldwork in support of the development and dissemination of the project results.
- Facilitate the PI's and Postdoc mobility period into our research laboratory, with the propose to provide training and perform measurents critical for the sucess of the proposed research.

Yours sincerely,

Prof. Michael Heap
Professor
University of Strasbourg

Michael Heap

Michael HEAP

Professor
heap@unistra.fr

Directeur
Renaud TOUSSAINT
Tél. +33 (0)6 73 14 29 94
renaud.toussaint@unistra.fr

Directrice adjointe
Séverine ROSAT
severine.rosat@unistra.fr

Directrice adjointe
Anne-Désirée SCHMITT
adschmitt@unistra.frr

Directeur adjoint
Sylvain WEILL
sylvain.weill@engees.unistra.fr

Responsable Administrative
Binta MESMACQUE
Tél. +33 (0)3 68 86 00 23
binta.mesmacque@unistra.fr

25.8.2022

To: The Academy of Finland

Contribution of Prof. Ilmo Kukkonen to the AKA Fellow application "Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings"

This is the statement of my commitment to contribute to the project "**Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings**" being submitted by Dr. Alan Bischoff. The suggested research on exploration of geothermal resources in crystalline rocks is very relevant for future sustainable energy production. The potential of crystalline bedrock as a thermal energy resource in Finland is huge. Dr. Bischoff's project is about finding and characterizing hydraulically permeable reservoir rocks, which are essential for the extraction of thermal power. The project has novel ideas and approaches for solving related problematics and I expect it will produce very useful contributions. My role in the project is the following:

- Provide expert advice on the thermodynamic characteristics of the Fennoscandian crust
- Facilitate knowledge, transfer and data from boreholes drilled in crystalline rocks
- Assess and help to define the types of geological structures that are potential crystalline reservoirs in Finland
- Discuss the geological and geomechanical parameters of altered-fractured crystalline reservoirs
- Assess to formulate theoretical simulations of different reservoir volumes vs. EGS lifetime scales
- Help integrate microscale petrographic and analytical (e.g. thin-sections, XRF, CT scan, Microprobe) observation with large-scale geophysical and field mapping datasets
- Attend workshops and fieldwork in support of the development and dissemination of the project results

Helsinki, 25 Aug, 2022

Ilmo Kukkonen
Professor in Solid Earth Geophysics
University of Helsinki
tel. +358405771262
e-mail ilmo.kukkonen@helsinki

School of Earth and Environment
Te Kura Aronukurangi

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Dr Andy Nicol
Professor of Geosciences
Phone +64 27 950 0282
Email: andy.nicol@canterbury.ac.nz

August 9th 2022

To: The Academy of Finland committee members:

I am pleased to provide a letter of support and collaboration for the project titled " Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings" submitted by Dr. Alan Bischoff.

I am the professor of Structural Geology at the University of Canterbury and have been leading multidisciplinary studies within the energy industry and research community for over 30 years. Alan Bischoff was employed at the University of Canterbury and we worked closely together from October 2015 to September 2021. During this time he held a Research and Teaching Assistant position in geoenergy, and completed his PhD in geological sciences. A critical contribution of his work was to co-design and co-lead large research grants designed to highlight the potential of geoenergy resources as reliable and sustainable energy sources. He has demonstrated great potential as an innovative researcher with capacity to lead multidisciplinary groups and supervise graduate and postgraduate students.

Since Alan has moved to Finland, we are maintaining collaboration on current projects led by the University of Canterbury and I would be pleased to formally collaborate with Dr Bischoff on his research into low-enthalpy crystalline reservoirs as a source of geothermal resources. These resources are of increasing interest in New Zealand where our geothermal industry is looking to extend operations beyond high-temperature areas that only occur on the Central North Island.

The purpose of this collaboration would be for me to assist Dr Bischoff in the structural and geophysical components of his project. These include:

- Support acquisition and analysis of structural data relevant to reservoir characterization,
- Expert advice interpreting complex brittle structures,
- Develop global models describing the geometry and interconnectivity of crustal fault zones and damaged zones in igneous intrusions,
- Facilitate access to up-to-date laboratory facilities, including modern equipment to measure the porosity, permeability and mechanical strength of crystalline rocks,
- Sharing data and knowledge about crystalline rocks and reservoir formation,
- Develop partnership co-supervising, advising and assessing MSc and PhD students.

Sincerely,

Andy Nicol

UNIVERSITY OF TURKU

Turku 10 August 2022

To: The Academy of Finland

From: Associate Professor Pietari Skyttä, University of Turku, Finland

Letter of collaboration - AKA Fellow application "Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings" by Alan Bischoff

With this letter I state the commitment of myself and the University of Turku to the project " Deep-HEAT-Flows: Discovering deep geothermal resources in low-enthalpy crystalline settings" being submitted by Dr. Alan Bischoff. The project is of great scientific interest and potential, and has parallels with both my scientific expertise and interests.

If the proposed project gets funding, I am committed to collaborate as described in the project description, and further detailed below:

- Support acquisition and analysis of structural data in the Fennoscandian Shield
- Guide selection of areas of interest for detailed structural analyses
- Provide expert advice interpreting complex brittle structures
- Facilitate access to up-to-date laboratory facilities, including modern equipment for thin-sections confection and description, and XRF analysis of crystalline rocks
- Share data and knowledge about crystalline rocks studied for the purposes of developing the radioactive waste disposal concepts in Finland
- Develop partnership within co-supervising, advising and assessing MSc and PhD students
- Act as a contact person with Alan Bischoff as he will contribute to teaching of geoenergy potential of crystalline rocks as part of BSc level courses in hydrogeology, included in the curriculum of the University of Turku

With best regards,

Pietari Skyttä

Apulaisprofessori / Associate professor (tenure)
Turun Yliopisto / University of Turku, SUOMI / FINLAND
Maantieteen ja Geologian laitos / Dept of Geography and Geology
Geologian osasto / Geology Section
Puh. / Tel. +358-40-5445973
www.utu.fi/sgg
https://geohouse.fi/

MONTAN UNIVERSITÄT LEOBEN

Lehrstuhl für Subsurface Engineering
Leitung: Univ.-Prof. Dipl.-Ing. Dr.mont. Robert Galler
Erzherzog-Johann Straße 3/III
A - 8700 Leoben
Tel.: +43 3842 402 3400
robert.galler@unileoben.ac.at
www.subsurface.at

To: The Academy of Finland

29 June, 2022

Dear Assessors,

I am pleased to provide a letter of support and collaboration on the project titled "Deep-HEAT-Flows:Discovering deep geothermal resources in low-enthalpy crystalline settings" submitted by Dr. Alan Bischoff.

This project has important implications for the wider application of geothermal energy in non-conventional, low-enthalpy areas. Austria has moderate-temperature geothermal resources in sedimentary basins as well as much un-explored and un-exploited areas of crystalline rock with significant tectonic and intrusive fracture damage. The work proposed by Dr. Bischoff is of great interest to me and my institution in terms of advancing geothermal potential in low-enthalpy crystalline rocks in general, as well as for the direct impact on use of geothermal in unconventional areas of Austria.

If this project is funded, my contributions will focus on the rock mechanics, fracture mechanics and rock mass geomechanics aspects of the work. As such, I will support Dr. Bischoff as follows:

- Provide expert advice regarding combining laboratory scale rock parameters and field fracture data to characterize the geomechanics of rock masses
- Provide expert advice on combining rock mechanical parameters with geochemistry to assess the impact of alteration on rock fracturing and permeability
- Support MSc and PhD students who are generating geomechanical models of the subsurface
- Providing access to computational software for generating rock mass constitutive models (Roscience RocData) and geomechanical numerical modelling (Rocscience RS2)
- Attend workshops and fieldwork in support of the development and dissemination of the project results

Best regards,

Associate Prof. Marlène Villeneuve, PhD, FHEA
Rock Mechanics and Rock Engineering

To: The Academy of Finland

British Geological Survey
Keyworth, Nottingham
NG12 5GG

Tel: +44 (0)115 936 3100 (x 3259)
E-mail caro@bgs.ac.uk

www.bgs.ac.uk
email: enquiries@bgs.ac.uk

30 August 2022

To whom it may concern,

I hereby wish to express my support for the proposal by Dr. Alan Bischoff entitled “Discovering deep geothermal resources in low-enthalpy crystalline settings”.

I am a Senior Geochemist at the British Geological Survey, and have a research interest in the geochemistry of fluid-rock reactions over a range of temperatures and pressures. I work in, and help manage, two experimental laboratories at the BGS; the Hydrothermal Laboratory, and the Hydrates and Ices laboratory.

I lead / have led, research projects investigating the geothermal potential of fractured granites in south-west England. Within these I have a personal interest in understanding geochemical reactions along fractures, and how leaching reactions contribute critical raw materials such as lithium to the geothermal waters. Thus, the project proposed by Dr. Alan Bischoff aligns well with my research interests and goals,

If the project is funded, I will aim to support it in the following ways:

- Offer expert advice related to characterising geochemical processes within and along fractures.
- Facilitate sharing of understanding of the fracture-hosted granitic geothermal reservoirs located within south-west England.
- Discuss the geological and geochemical parameters that can form altered-fractured crystalline reservoirs.
- Offer practical knowledge on running successful geochemical laboratory experiments.
- Participate in workshops and other activities, where possible, designed for sharing knowledge between this and other projects with a view to maximising scientific understanding.

Yours sincerely

Dr Chris Rochelle