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Geothermal: The Next Generation - Advancing the Understanding of New Zealand's Supercritical Resources

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ABSTRACT

New Zealand is endowed with generous geothermal resources. Currently untapped, NZ's deeper, supercritical geothermal resources have the potential to provide a near- unlimited source of renewable energy, with ten times more energy than conventional geothermal. New Zealand's unique tectonic setting with its active rifting arc produces voluminous magma and outstanding heat flow. It delivers exceptional opportunities for geothermal development and has placed New Zealand among the leaders in geothermal energy technology for the past 60 years. Our present level of scientific understanding, however, is insufficient to offer industry-ready solutions for NZ. Our multidisciplinary programme aims to resolve the critical, underpinning geological, geochemical and technological challenges – unknown in conventional geothermal – to enable future NZ generations to sustainably use supercritical resources for electricity generation and high-temperature industrial applications, while minimising carbon emissions.

Started in October 2019, this research programme – building on over a decade of research – aims to minimise exploration and technological risks by detailing heat transfer at significant depth; interactions between New Zealand rocks and fluids at supercritical conditions; modelling system sustainability; and delineating the potential of these resources.

We assembled New Zealand and overseas geophysicists, geologists, experimental geochemists, modellers, as well as economic and Māori strategic investment advisors. Here we present an update on the main objectives, relevance, future linkages and the first results 2.5 years into this challenging and strategic new scientific endeavour. Aotearoa New Zealand's supercritical journey is underway and on display through www.geothermalnextgeneration.com and associated social media connections.

1. INTRODUCTION

Early supercritical projects are expected to have long lead times because these hot conditions (>400°C) are yet to be encountered for energy production in Aotearoa New Zealand. Supercritical or superhot energy is a logical next step in maintaining and expanding existing geothermal infrastructure in a producing geothermal field, providing an energy refresh, whilst retaining the existing land footprint. Unknowns include well design, fluid handling, appropriate surface facilities for energy transformation, consenting, cost and more. We aim to advance understanding and knowledge as part of determining if deep superhot is a viable geothermal energy opportunity for Aotearoa.

Geothermal: The Next Generation is divided into three key projects that reflect New Zealand and worldwide needs. As part of Project EXPLORE we have been improving our geophysical and computer modelling to de-risk and target future exploration areas. We have selected target sites that combine social and scientific feasibility, and conversations with possible end users and stakeholders are progressing.

Under Project UNDERSTAND, the most important outcome is the establishment of a unique research facility for experimentation on fluid - rock, fluid - infrastructure interactions under supercritical conditions. This is providing a fundamental resource for the testing of materials and will support engineering projects into the future.

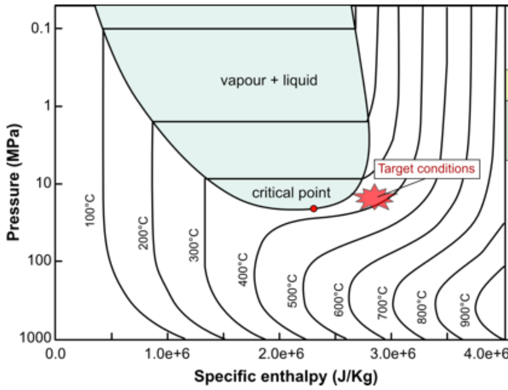
Long term strategic thinking is delivered under Project INTEGRATE. To align hot, deep ultra-hot geothermal with New Zealand's low carbon economy and energy sector aspirations, sector-wide roll out of supercritical geothermal operations needs to occur before 2050. Working backwards, pilot and scale up demonstration of supercritical energy production would be needed by about 2040, and thus, the first exploration wells need to be drilled by about 2030. A supercritical geothermal strategy for Aotearoa New Zealand is being developed, and preparatory and pre-planning work, including an International Continental Scientific Drilling Program proposal, is underway (e.g., geoscience, exploration, well design, regulatory assessment, social engagement) to work towards drilling a deep exploratory well in the next decade.

Geothermal: The Next Generation is a five-year programme (2019-2024) funded by the New Zealand Ministry of Business Innovation and Employment (MBIE) and addresses the geological, geochemical and technological challenges to go beyond conventional geothermal systems and tap into hotter, deeper supercritical energy resources.

Here we are presenting the annual updates of Project 1: EXPLORE for New Zealand future geothermal resources, Project 2: UNDERSTAND the thermochemistry of supercritical resources and Project 3: INTEGRATE translate and communicate knowledge.

2. SCIENCE PROBLEMATIC

Supercritical resources are the focus of global research towards a “frontier” energy source (Dobson et al., 2017; Elders et al., 2014; Friðleifsson et al., 2007; Moore and Simmons, 2013; Reinsch et al., 2017; Watanabe et al., 2017). Supercritical fluids exist at temperatures and pressures above the critical point where distinct liquid and gas phases don’t exist (for pure water, >374°C and >221 bars) (Palmer et al., 2004). They exhibit higher heat-content and lower density and have the potential to generate around ten times more energy than conventional geothermal for the same amount of extracted fluid.



P, T(bar, °C)	Enthalpy (KJ/kg	Dynamic Viscosity (10⁻⁵ Pa.s) (KJ/kg	Ratio (Enthalpy/ viscosity)	Ratio to base case
100, 250	1086	10.0	108.8	1.0
100, 400	3100	2.45	1265	11.6
200, 400	2820	2.60	1085	10.0
300, 400	2162	4.34	498	4.6
400, 400	1934	6.13	315	2.9
500, 400	1878	6.79	277	2.5

Relative ease of extracting energy from a kg of fluid at 400°C. Yellow cells are conventional reservoir conditions. Green cells represent the targeted conditions (100 to 200 bars for 400°C) assuming similar permeability.

Figure 1: Optimal P, T conditions to target supercritical reservoirs in the TVZ.

Three issues make utilisation of supercritical fluids (globally) challenging:

1. Supercritical conditions are achieved when reservoirs are located near intrusions of magma (Scott et al., 2015, 2016, 2017), or at greater depths in the Earth’s crust (http://www.thinkgeoenergy.com/new-study-supercritical-geothermal-fluids-more-common-than-expected/; Agostinetti et al., 2017) where the rocks change from being brittle to ductile. Depth, poor permeability and vicinity to magma lead to drilling and reservoir-engineering complexities (Agostinetti et al., 2017; Ásmundsson et al., 2013; Benderitter et al., 1990; Bignall and Carey, 2011; Hashida et al., 2000; Hauksson et al., 2014).

2. The chemical and fluid-dynamic behaviour of supercritical fluids with the surrounding rocks is unknown, but different from that seen with conventional geothermal fluids (Tsuchiya et al., 2016).

3. While some countries have accessed supercritical or superhot fluid conditions with limited success, their expertise **is not directly-translatable** given New Zealand’s distinctive geological environment.

This programme is designed to a) locate supercritical fluids and delineate potential resources; b) investigate the distinct chemical characteristics of these reservoirs; and c) integrate the knowledge from the above to allow supercritical utilisation as an energy resource. Our approach is synergetic between understanding the crust, modelling heat transfer and geochemical processes at supercritical conditions. The programme will provide results of thermodynamic and chemical processes in the crust to 4-10 km depths that permit forecasting for drilling, modelling of resources, and regulatory controls.

The development of supercritical resources is a global challenge (Reinsch et al., 2017). Supercritical systems at >400°C have been investigated in several volcanic areas including Italy, Iceland, Japan, Mexico and the USA (Friðleifsson and elders, 2005; Friðleifsson et al., 2014; Asanuma et al., 2012; Batini et al., 1983; Bertini et al., 1980; Chu et al., 1990; Garcia et al., 2016; Ikeuchi et al., 1988, Lovenitti et al., 1985; Muraoka et al., 1998, 2014; Sigmundsson et al., 2016). These investigations suggest that optimal supercritical resources are located closer to magmatic heat souces than conventional systems (Scott et al., 2015; Friðleifsson et al., 2005). New Zealand’s deep (>6km) magmatic conditions do not create drillable and permeable supercritical reservoirs, however; we **hypothesise** that the presence of buried shear zones or shallow intrusions favouring heat transfer from the deep magma reservoir to shallower conditions provides drillable targets.

We will thus explore this hypothesis by characterising the location and behaviour of heat and fluid transfer around magma bodies or in shear zones under supercritical conditions (Figure. 2).

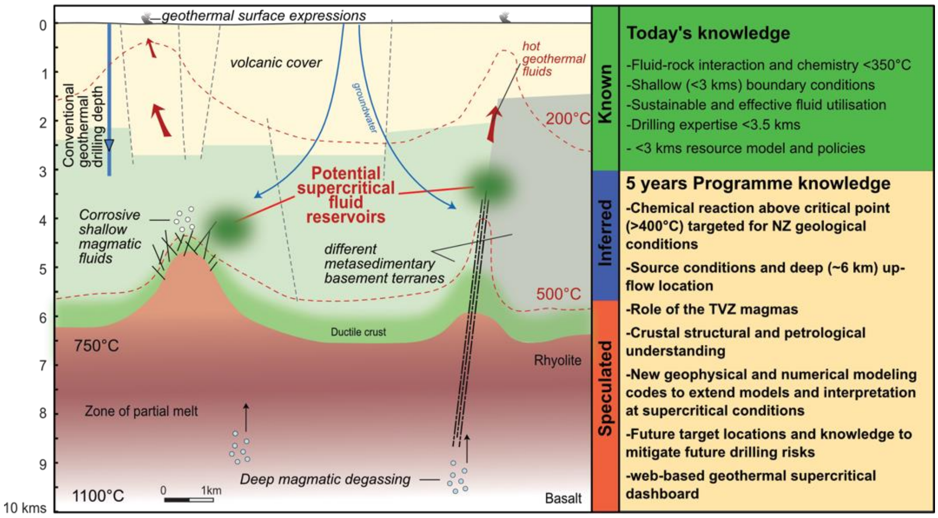


Figure 2: Conceptual model of deep supercritical geothermal systems in the TVZ presenting on the right the level of uncertainties in today's scientific knowledge (know, inferred, speculated) and the future knowledge after the 5 years programme that will be acquired by this research.

3. KEY ACHIEVEMENTS

Geothermal: The Next Generation is designed to: a) locate the most prospective location(s) for accessing supercritical fluids in the earth in New Zealand's Exclusive Economic Zone and delineate potential resources; b) investigate the chemical characteristics of these fluids and their behaviour during reinjection (including non-condensable gas); and c) integrate the knowledge from the above to facilitate supercritical energy resource utilisation as part of New Zealand's push to "carbon zero" by 2050.

Scientific communications on supercritical and geothermal in general have been released via. https://www.geothermalnextgeneration.com. More than 50 knowledge updates have been posted. These contain links to peer reviewed journals (or open access journals), public conference proceedings and videos of the presentations, public reports, and case studies. We believe that communication around our science, the challenges that it creates and our work is key to a better engagement and social acceptance as well as strategic leveraging.

3.1 Public key achievements

1. A compilation of dozens of aeromagnetic surveys over the upper North Island as a fundamental exploration data set has been completed. A procedure for merging gridded airborne and shipborne magnetic data over the upper North Island has been formulated using Geosoft scripts (Barreto and Caratori Tontini, 2022). The two main products are an integrated total magnetic intensity (TMI) Geosoft grid with 100 m cell size and UTM 60S projection on the NZGD2000 datum and a master database containing the data from 37 individual surveys and from a TMI regional drape grid created from three regional grids.

The integrated TMI grid and database is currently updated as new magnetic data become available by following the steps outlined in the study of Barreto and Caratori Tontini (2022). The procedures described by the authors can also be applied for the creation of integrated magnetic grids for a larger area such as the whole of New Zealand or from any geographic area. The processing sequence is also adaptable to produce other geophysical products, where single elevation drape grids are created for various geophysical analysis such as frequency analysis and curie point depth calculations.

2. A work detailing the evolution of magmatic volatiles in the Taupo was published (Sharpe et al., 2022). This study provides insights on the nature and composition of potential magmatic fluids presently degassing under the TVZ.

We documented sulfur (S), chlorine (Cl), and fluorine (F) concentrations in a range of host materials in eruptive deposits from Taupō volcano (New Zealand). Sulfur and halogen concentrations each follow distinct concentration pathways during magma differentiation in response to changing pressures, temperatures, oxygen fugacity, crystallising mineral phases, the effects of volatile saturation and the presence of an aqueous fluid phase. Sulfur contents in the basaltic melt inclusions (~2000 ppm) are typical for arc-type magmas, but drop to near detection limits by dacitic compositions, reflecting pyrrhotite crystallisation at ~60 wt. % SiO_2 during the onset of magnetite crystallisation. In contrast, Cl increases from ~500 ppm in basalts to ~2500 ppm in dacitic compositions, due to incompatibility in the crystallising phases. Fluorine contents are similar between mafic and silicic compositions (<1200 ppm) and are primarily controlled by the onset of apatite and/or amphibole crystallisation and then destabilisation. Sulfur and Cl partition strongly into an aqueous fluid and/or vapour phase in the shallow silicic system.

3. The Experimental Geochemistry Laboratory at the GNS Science Wairakei Research Centre has been conducting continuous flow experiments at supercritical pressure and temperature conditions like those expected in NZ supercritical reservoirs (high temperature but low pressure). The experimental apparatus is unique in the world and was especially designed and built by Parr Instruments (USA) to conduct mineral solubility and water-rock interaction experiments at these conditions.

4. An experimental study has been completed to test indium (In) and rhenium (Re) as potential geothermal tracers up to super-hot and supercritical conditions. The preliminary results show that Re is potentially a suitable candidate, however, In is not (Sajkowski et al., 2022). The flow-through experiments were conducted in the temperature range of 200–400°C, and in presence of a NZ greywacke rock substrate. The results indicate that Re behaves conservatively, in the presence of the rock and H_2S up to supercritical conditions. But at these conditions, the low density of the fluid results in the loss of Re, making it unsuitable as a tracer under these conditions.

5. A comprehensive reactive transport model was built and calibrated in TOUGHREACT™ to numerically simulate fluid-rock reactions between basalt and water at subcritical conditions (350°C, 500 bar) (Altar et al., 2022). The results represent the calibration of a numerical model with actual laboratory experimental results. The mineral reactions were found to be largely kinetically controlled based on the model results. Mineral dissolution and precipitation rates are dependent on the rate constant parameters, the reactive surface area, and the chemical saturation state.

6. To advance well design, two synthetic well prognoses have been developed, structured to define the conditions expected to be encountered and to be contained by a supercritical geothermal well in the TVZ drilled to a depth of ~6 km (Carey et al., 2021). Two sites were selected for the hypothetical wells: i) in a location midway between Ohaaki and Ngatamariki and ii) on the margin of the Rotokawa geothermal system. Pressure-depth conditions expected are hydrostatic from the surface down to the metasedimentary contact, and probably sub-hydrostatic under the metasedimentary rocks. Though it is challenging to predict the composition of the supercritical fluids, we propose an analogy here based on the physicochemical conditions of supercritical fluids observed in other parts of the world.. Equipment, materials and drilling and well testing procedures all need to be developed further as part of activity that is beyond the scope of the GNG programme.

4. RESEARCH, SCIENCE AND TECHNOLOGY

4.1 Project Explore preliminary achievements

Geophysics, structural, geological, and modelling work have progressed in the last 3 years. A combined discipline approach workshop between scientists led to the selection of geothermal exploration targets in order to locate a potential supercritical exploration well. The Southern Taupo Volcanic Zone (TVZ; Rotokawa, Tauhara, Wairakei geothermal areas), Ohaaki geothermal area, and the North of Okataina area are proposed as key exploration locations.

This will support the engagement and strategic work underway in INTEGRATE.

A new Total Magnetic Intensity grid, built on the North Island TMI integrated grid (Fig. 1) that includes offshore magnetic data that has been constructed for use in Curie Point Depth (CDP) calculations. This new grid is the first update to part of the Zealandia magnetic map in more than 20 years. This map provides a fundamental geoscience resource for the Zealandia continent. Three-D inversion work of gravity and magnetic anomalies in Wairakei-Tauhara and Rotokawa geothermal fields has commenced. These models will extend knowledge based on extensive drilling in these fields and extend our interpretations to depths beyond drill hole penetration.

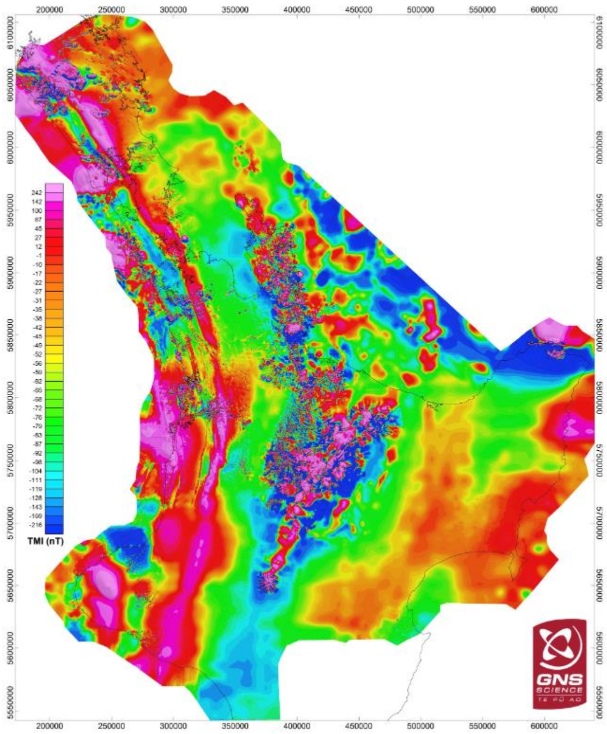


Figure 1: Map showing TMI_integrated_final.grd grid, the product of integrating 37 magnetic micro-survey datasets over the TVZ and adjacent areas with a regional TMI grid (modified from Barreto and Caratori Tontini, 2022).

The magnetotelluric team implemented the FEMTIC MT inversion code. This code allows topography to be incorporated and the mesh to be adaptively refined around areas of interest making computation more efficient and results better able to be placed in context with other models. The first use of this capability at Mt Tongariro has now been completed and the code will be applied to Wairakei-Tauhara-Rotokawa geothermal field data to image fluid and melt distribution in detail.

High resolution seismic tomographic techniques have been developed and applied at Okataina Volcanic Center to the north, and these are now being applied at finer scale to our target regions. These models seek out seismic anomalies caused by fluids and gas within the crust. The combined gravity/magnetic/MT and seismic tomography models will be important inputs for future well targeting.

Improved definition of buried basement terrane location through new petrographic studies of xenoliths has yielded insights into the likely terranes to be encountered at depth within the target areas. Future work into the permeabilities of these terranes, upscaling the team's outcrop studies to high temperature and pressure conditions will determine their suitability as reservoir host rocks.

The modeling team successfully modelled the thermal conditions surroundin a deep cooling magmatic mush and will improve the modelling by including magmatic degassing next year.

4.2 Project Understand preliminary achievements

Experimental work has continued in Project UNDERSTAND including two water-rock interaction experiments using NZ basement greywacke rock (the main injection aquifer for TVZ geothermal power stations) and geothermal brine. One experiment was conducted at the supercritical conditions of 400^{o}C and 250 bars pressure. This experiment shows extensive alteration/reaction between the rock and brine. A companion experiment was completed at the subcritical conditions of 350^{o}C and 300 bar pressure for comparison between subcritical (conventional geothermal) and supercritical results. The reactions differ markedly due to the low density of the water phase at supercritical conditions.

The supercritical high-temperature reactor set up in the previous year has been used this year to measure the solubility of quartz (a ubiquitous mineral in geothermal systems both subcritical and supercritical). The results of this experimental work were used to refine the experimental method which uses a unique continuous flow reactor. We have now successfully measured the solubility of quartz in the region of 375 – 600^{o}C and 200 – 270 bar. A publication containing the experimental results is planned for 2023. The data will be fundamental information for engineers and geochemists working on supercritical fluid production and utilisation.

An experimental study was completed in 2021 – 2022 on the use of rhenium (Re) as a potential tracer chemical under geothermal conditions both subcritical and supercritical. The results showed that Re was lost once the fluid became supercritical at low pressure because of the significant decrease in density. This indicates that Re would not be expected to be applicable as a tracer at supercritical conditions but there may be some potential at subcritical conditions. Experiments are currently underway to test naphthalene as a potential tracer under supercritical conditions.

The comprehensive reactive transport model was built and calibrated by the team at Auckland University using TOUGHREACT^{TM} to numerically replicate the results of a detailed laboratory experiment on the interaction of basalt and water under subcritical conditions. The results were published this year in *Geothermics* (Altar et al. 2022). During this past year a second model was built and calibrated to numerically replicate the results of a laboratory experiment reacting basalt with water at supercritical conditions (400^{o}C, 500 bar). The models used actual experimental data for calibration meaning that they can simulate fluid-rock interactions in the subsurface based on true mineral reactions. This numerical approach will be used to model 3D reservoirs in the future.

4.3 Project Integrate preliminary achievements

The GNG Integrate team held six internal workshops through the period. Two critical steps were initiated / developed more strongly through 2022:

Inventory of supercritical resource potential – An approach to developing an inventory for New Zealand has been established based on The United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 incorporating Specifications for its Application to Geothermal Resources which provides an internationally recognized methodology to classification and categorisation. The framework provides a systematic way of moving an ultra-hot geothermal project from conceptual through to operational. For a national assessment the framework envisages an aggregation of individual projects.

Market Propositions – We are preparing a market proposition for the development of ultra-hot geothermal energy in New Zealand, with work underway to explore what the proposition(s) for the use for New Zealand might be.

As part of GNG work Project Waiwhatu (fluid from the core) - geothermal Reo was initiated. In this project, key concepts, words or phrases that are meaningful and useful for geothermal and the GNG project team are being translated into Te Reo. This project was born out of discussions with Uenuku Fairhall, a Te Reo expert, as he was translating the GNG website. He expressed his difficulty in trying to source meaningful and relevant words to define the scientific terms the geothermal sector and the GNG project are using. The true test will be in the uptake and use of the words and concepts with time.

Forty-five knowledge updates to the Geothermal: The Next Generation website have been posted. Social media posts have been made through the Geothermal Next Generation Facebook and LinkedIn pages as well as the private profile Isabelle Chambefort.

5. ENGAGEMENTS AND FORWARD LOOKING

We continue to have end user engagement and communication via hui (meetings), the web site and social media platforms. We continue our effort based on our Engagement Strategy established during the first year of the programme with tailored engagement efforts to different types of stakeholders.

The priority of each group guides the mechanisms and level of engagement, and hence the programme's effort and investment (e.g., time, funding, resourcing) in each group.

Higher priority stakeholders are those who:

- make decisions that could be influenced by an improved understanding of supercritical science
- can make or influence national policy and investment
- have a direct interest in the research outcomes
- have a direct interest in supporting or partnering with the research
- can help promote the key results and messages.

Today, there are more questions than answers as to what the superhot / supercritical geothermal future for New Zealand might look like, and a collaborative, consultative process is essential to develop the most promising pathway for delivery of this geothermal technology for New Zealand.

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