

Geothermal: The Next generation, Advancing the Understanding of New Zealand's supercritical resources – Programme update

Isabelle Chambefort¹, Craig Miller¹, Bruce Mountain¹, Brian Carey¹ and the Geothermal: The Next Generation Team^{1,2,3,4,5,6,7}

¹ GNS Science, New Zealand

² Victoria University of Wellington, New Zealand

³ ETH Zurich, Switzerland

⁴ University of Auckland, New Zealand

⁵ Upflow, New Zealand

⁶ Bridger Limited, New Zealand

⁷ Traverse Environmental, New Zealand

i.chambefort@gns.cri.nz, geothermalnextgeneration@gns.cri.nz

Keywords: *Geothermal: the Next Generation, Explore, Understand, Integrate, Supercritical.*

ABSTRACT

New Zealand is endowed with generous geothermal resources. NZ's deeper, currently untapped, supercritical geothermal resources have the potential to provide a source of renewable energy. New Zealand's unique tectonic setting, with its active rifting arc, producing voluminous magma and outstanding heat flow, delivers exceptional opportunities for geothermal development.

Started in October 2019, the Geothermal: the Next Generation MBIE research programme aims to resolve the critical geological, geophysical and geochemical questions on supercritical reservoir formation, and identify the technological challenges of establishing supercritical geothermal as part of the solution for Aotearoa's carbon neutral energy future.

The research team is composed of New Zealand and overseas geophysicists, geologists, experimental geochemists, reservoir and geodynamic modellers, as well as, economic and Māori strategic investment advisors. Here we present an update on the main objectives, relevance, future linkages, and the initial results three years into this challenging and strategic 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 very hot conditions (>400°C) are yet to be encountered for energy production in Aotearoa New Zealand. Supercritical 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 drilling location, well design, drillability, fluid handling, appropriate surface facilities for energy transformation, consenting, cost and more. We aim to advance understanding and knowledge as part of determining

if supercritical is a viable geothermal energy opportunity for Aotearoa.

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. 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 45 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.

2.1 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 fugacities, 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. % SiO₂ 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.

2. The Experimental Geochemistry Laboratory at the GNS Science Wairakei Research Centre has been conducting continuous flow experiments at supercritical pressure and temperature conditions similar to 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.

3. 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 H₂S 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.

4. 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.

5. 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.

3. RESEARCH, SCIENCE AND TECHNOLOGY

3.1 Project Explore preliminary achievements

Geophysics, structural, geological, and modelling work have progressed this year under EXPLORE. 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.

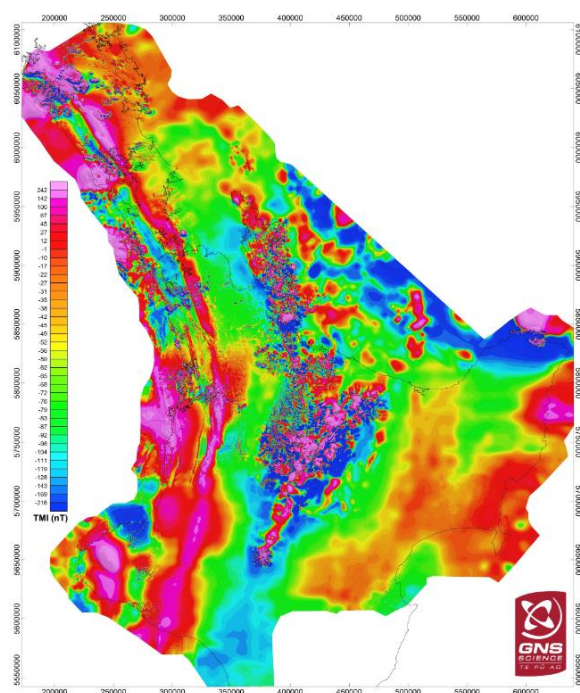


Fig 1: Map showing TMI_integrated_final.grd grid, the product of integrating 37 magnetic micro-survey datasets over the TVZ and adjacent areas with a regional TMI grid (modified from Barreto and Caratori Tontini, 2022).

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 surrounding a deep cooling magmatic mush and will improve the modelling by including magmatic degassing next year.

The team also welcomed the collaboration of MSc students Siru Jylhäkangas (Comparing theoretical elastic anisotropy with seismic anisotropy in the Taupō Volcanic Zone, with Prof Martha Savage) and Keiha Nicols (Early andesite and onset of the TVZ with Prof Colin Wilson) from Victoria University of Wellington.

3.2 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°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°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°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 TOUGHTREACT™ 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°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.

3.3 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.

4. ENGAGEMENTS AND FORWARD LOOKING

We continue to have end user engagement and communication via hui, 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 ultra-hot 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.

ACKNOWLEDGEMENTS

Geothermal: The Next Generation research programme is funded by New Zealand's Ministry of Business, Innovation and Employment (MBIE, under contract C05X1904).

REFERENCES

- Altar, DE, Kaya, E, Zarrouck, SJ, Passarella, M, Mountain, BW. 2022. Numerical geochemical modelling of basalt-water interaction under subcritical conditions. *Geothermics* 105, 102520. <https://doi.org/10.1016/j.geothermics.2022.102520>
- Barreto, J., Caratori Tontini, F. 2022. Total magnetic intensity grid of the upper North Island New Zealand. Lower Hutt (NZ): GNS Science. 29 p. (GNS Science report; 2021/47). doi:10.21420/A520-NK43.
- Carey, B., et al, 2021. Prognoses for two supercritical well designs. Lower Hutt (NZ): GNS Science. 14 p. (GNS Science report; 2021/36).
- Sajkowski, L., Kamiya, A., Mountain, B.W. 2022. An experimental study on the potential of Rhenium and Indium as geothermal tracers. GNS Science Report 2022-23. DOI: 10.21420/HNET-JY77.
- Sharpe, M.S., Barker, S.J., Rooyakkers, S. M., Wilson, C.J.N., Chambefort, I., Rowe, M.C., Schipper, C.I., Charlier, B.L.A., 2022, A sulfur and halogen budget for the large magmatic system beneath Taupō volcano, Contributions to Mineralogy and Petrology. <https://doi.org/10.1007/s00410-022-01959-w>