GEOTHERMAL: THE NEXT GENERATION

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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 aim 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.

This new 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 the main objectives, relevance and future linkages of this challenging new science endeavour.

1. INTRODUCTION

Climate change is the defining challenge of our time. Under the Paris Agreement, 184 countries are committed to reducing carbon emissions. NZ has set a target of 100% renewables by 2035 and a 'Net-Zero Emissions Economy' by 2050. Geothermal is instrumental in achieving this goal, but the critical challenge is to go beyond conventional geothermal to tap deeper, supercritical resources.

Innovation is key to NZ's low-carbon transition. Unlocking NZ's deep (>4 km) supercritical geothermal resources requires fundamental research and significant technological innovation.

In 2018, NZ generated 43,000 GWh of electricity (5M home equivalent, 7,373 GWh from geothermal, 17.1 % total generation). On current trends, conventional geothermal, hydro, solar and wind cannot outpace non- renewables. To replace all greenhouse gas emitting energy New Zealand requires more than 17,000MW total generation. To achieve 100% renewable energy in 15 years, and support a low carbon future, New Zealand must fundamentally transform its energy sector.

Key to this paradigm-shift will be accessing New Zealand's abundant energy resources within the Earth. Supercritical fluids have 10 times more energy than conventional geothermal fluids (Dobson et al., 2017). The immediate impact from our programme will be globally-novel knowledge/ approaches/ technology-pathways to resolve geological, geochemical and technological challenges unknown in conventional geothermal.

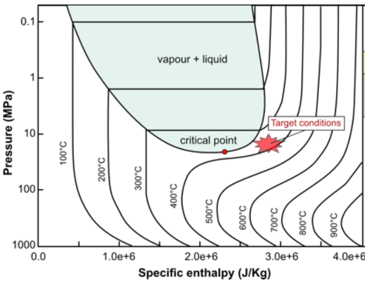
'Deep geothermal' will enable a step-change in NZ development/use of 'green technologies' (e.g. hydrogen cells), create high-value exportable 'know-how' and jobs, and support direct-use applications of high-value to industry, Māori, and regions. Ensuring security of supply while lifting GDP and community well-being will ensure a just-transition to a low-carbon economy.

Our challenging programme aims to adapt and advance global research-horizons to locate/delineate New Zealand's supercritical resources, and characterise their fundamentally-unique chemical and fluid- dynamic properties. It also investigates the potential for reinjection of carbon dioxide from supercritical energy generation to enable emissions-free 'deep heat' energy.

Drawing on insights from decades of previous research, we will develop/apply novel magmatic and hydrothermal numerical modelling to delineate and characterise inferred supercritical resources in the Taupō Volcanic Zone. Leveraging expertise at ETH Zurich, University of New South Wales, GFZ-Potsdam, and Japan, as well as NZ's unique experimental geochemistry laboratory, the programme will also investigate magmatic fluids and resulting water-rock interactions in the supercritical-domain to assess potential exploration approaches and technology pathways. We will develop and establish an engagement strategy to communicate scientific results to stakeholders, next users, decision-makers and the public. Combined research areas are required to unlock the next-generation potential of NZ's geothermal 'deep-heat' resources.

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 Taupō Volcanic Zone (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 geothermal fluids 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 sources than conventional systems (Scott et al., 2015; Friðleifsson et al., 2005). New Zealand's deep (>6 km) 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).

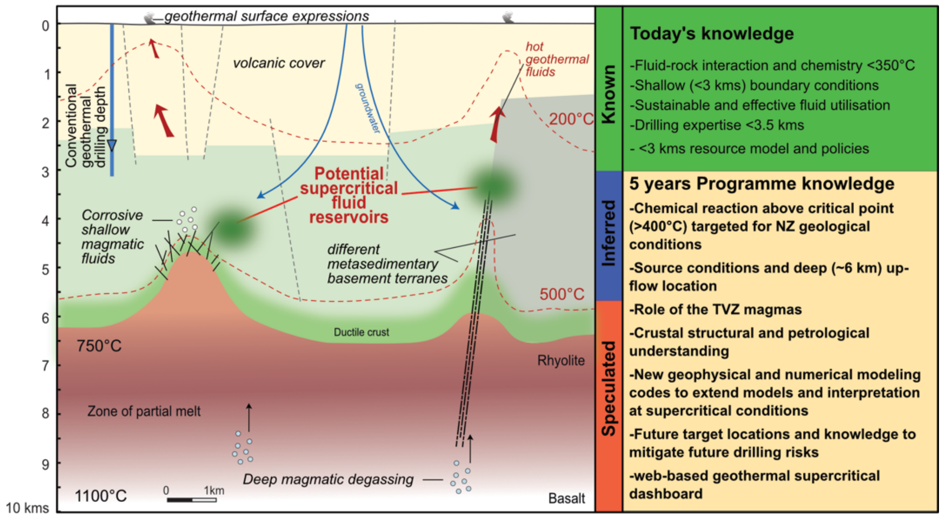


Figure 2: Conceptual model of deep supercritical geothermal systems in the TVZ presenting on the right the level of uncertainties in today's scientific knowledge (know, inferred, speculated) and the future knowledge after the 5 years programme that will be acquired by this research.

Development of New Zealand's existing geothermal resources has depended in large part on laboratory research to determine the chemical behaviour of geothermal fluids (MBIE Contestable programme Supermodel C05X1306), the effects of fluid-rock interaction, and predicted changes in rock properties during fluid extraction and injection (MBIE Contestable Empowering geothermal energy C05X1706). We will leverage on this laboratory expertise combining it with international skills to acquire the foundational knowledge required to discover, develop and maintain supercritical geothermal resources. We will expand our approach by testing injection of Non-Condensible Gas into various reservoir rocks providing direct knowledge on future Greenhouse gas emission reinjection initiatives.

Our approach builds on decades of research and New Zealand expertise in geothermal utilisation of the TVZ (Bignall and Carey, 2011; ECLIPSE MBIE Endeavour Programme. RTVU1704; RSNZ Te Aparangi Marsden Fund Superhot fluids: The origin and flux of natural greenhouse gases in volcanic areas, MFP-GNS1802; GNS Strategic Science Investment Funds Understanding Zealandia and New Zealand's Geothermal Future; Chambefort and Bignall, 2016; Wilson and Rowland, 2016; Driesner, 2010, 2013; Driesner et al., 2015; Regenauer-Lieb et al., 2014). We will tailor magmatic and hydrothermal numerical models to this region, and apply geochemistry, geophysical, and geological methods to comprehensively inform on NZ's supercritical geothermal potential.

3. INTERNATIONAL RESEARCH CONTEXT AND LEVERAGE

New Zealand has led the world in geothermal science research for 60 years and developed strong relationships with geothermal countries. Built on years of investment and national and international collaborations, the team's worldwide positive reputation attracts international collaborators. We will leverage off magmatic and hydrothermal numerical modelling skills at ETH Zurich and University of New South Wales, geochemistry expertise from GFZ-Potsdam, and geophysics and geological resources from Japan.

We anticipate academic and applied impacts with global scope through our collaborations with researchers at the US Department of Energy; the Great Basin Center for Geothermal Energy (USA); ETH-Zurich (Switzerland); the University of New South Wales and its EUREKA programme; the AIST and TITECH programs in Japan; and the University of Iceland. Together we will identify initiatives, challenges, opportunities and share knowledge on novel uses of geothermal-sourced supercritical heat. Through the power of combined international expertise, this project has the potential to become a lighthouse example of how international collaboration (within IPGT) can lead to major synergistic advances that none of the involved countries would be able to solely achieve. It is also a reflection of the international challenges posed by supercritical geothermal.

4. THE APPROACH

Our approach integrates field data, laboratory data, and numerous model outputs to accurately delineate the supercritical resource. Laboratory studies and numerical models are critical and inevitable methods to understand an inaccessible region several kilometres below even conventional geothermal fields.

The programme's three complementary research aims: *Explore, Understand* and *Integrate*. While *Explore* and *Understand* deliver underpinning scientific information, *Integrate* will bring the information together, so that the research aims collectively deliver on our research objective.

1. EXPLORE *for future geothermal resources*

Using existing and newly-collected geological and geophysical data from the central TVZ, the structure of the basement and the influence and location of the magmatic bodies will allow us to identify geological constraints on supercritical reservoirs. This will support future drilling and resource strategy.

This aim tests our key hypothesis that optimal supercritical conditions are found where magmatic heat encounter buried structures above the ductile region. Modelling of thermomechanical and thermochemical processes in shear zones and heat transfer from magma will identify the most likely locations of supercritical resources. Our approach builds on understanding and modelling the geology, geophysics, and geochemistry beneath known geology at the provincial scale to understand the fundamental control on heat transport through the volcanic region. Using geophysical, geological and modelling techniques we will identify the geological limits and risks of supercritical heat stocktaking.

2. UNDERSTAND *the thermochemistry of supercritical resources*

Exploration for and utilisation of supercritical fluids is dependent on accessible and high quality thermodynamic data and a thorough understanding of the effects of fluid-rock interaction. Fluid and rock chemistry will change as supercritical reservoir conditions are reached; these changes can be used as exploration tools. Economic viability and sustainability of the development is fundamentally influenced by the active physicochemical processes during production and re-injection, and is thus essential information. Our goal is to acquire these essential thermochemical constraints in the New Zealand context.

Experimental thermochemistry will define chemical species distribution and fluid-rock interactions due to re-injection. We will model the behaviour of dissolved and volatile species in the transition from ductile to brittle conditions. Incorporation of these data into numerical models will greatly facilitate resource definition and prediction. As a consequence of our experimentation plan we will test CO_2 sequestration potential in supercritical rocks providing constraints on emissions capture. Modelling the geochemical behaviour of CO_2 in the supercritical to subcritical transition will identify any risks involved.

3. INTEGRATE *and translate knowledge*

We will establish a coordinated strategy, educate and promote enhanced and integrated utilisation of New Zealand's high enthalpy (supercritical) geothermal systems. A web site will offer a geothermal dashboard with living documents, reports, publication and brochure for end user to utilise. By the conclusion of this step, we will have identified and communicated findings concerning development opportunities for industry, iwi and land owners; factors that might limit resource use; delivered guidance to overcome possible geoscience, engineering and regulatory challenges; presented information (via hui, web-based media, published case studies and presentations) concerning the feasibility, national and regional impact of commercial development anticipated from the utilisation of New Zealand's renewable, supercritical geothermal resources; and

established processes and effective mechanisms for the ongoing communication of our science and policy impact, to Government, regional authorities, iwi, landowners, geothermal users, schools and general public.

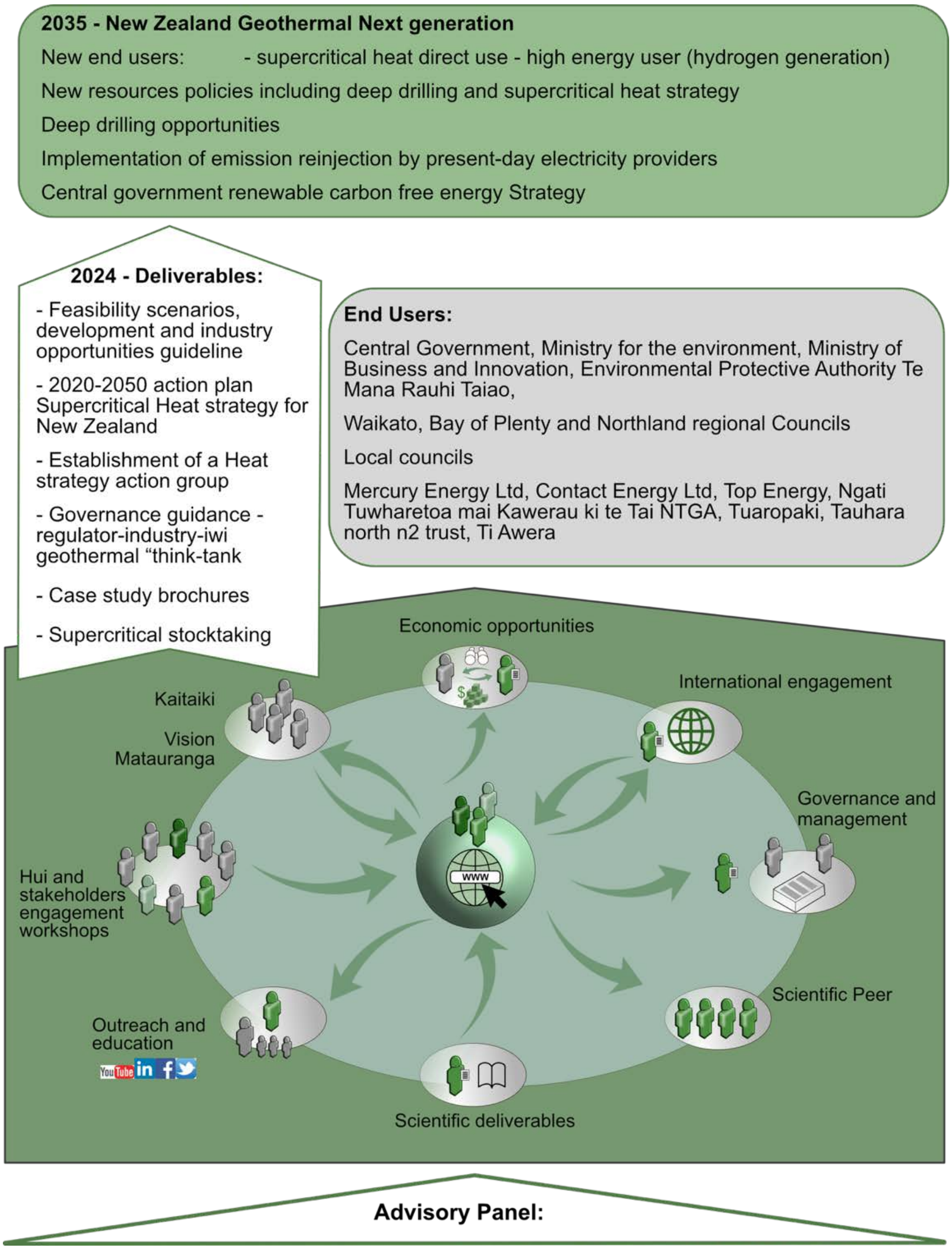


Figure 3: Schematic representation of Geothermal: The Next Generation engagement strategy

Within our team we have incorporated experts in business and economic development, Kaitiaki advice, engineering and social sciences. We will establish a coordinated strategy between communities, Iwi, regional councils, and power companies, to communicate, educate and promote the future utilisation of New Zealand's supercritical geothermal systems.

The end of programme will have delivered functional knowledge of New Zealand's supercritical resource, ready and in the hands of stakeholders for uptake in the next stage development. As a supercritical industry does not exist yet, we will work with stakeholders most likely to invest in the opportunity and/or benefit from it. Of these stakeholders, potential electricity generators are critical to the successful implementation, as direct-heat users are mostly unable to produce the substantial investment for resource development. Related to developing a new resource are policy makers, who need to be familiar with the research to develop appropriate policy.

Although we will deliver highly applied research, it is also of fundamental nature due to the novelty of the science. Therefore, this stage of research is built around prompt and regular dissemination of results, feedback sessions, hui, workshops and seeking international feedback on latest developments in science, engineering, and industry. The high frequency of wide stakeholder engagement is also designed to deal with unexpected research findings, barriers to implementation, or market developments, allowing the wider research/stakeholder team to respond in a timely fashion. The deep-seated interest by local iwi in development of their land and people, and the opportunity to progress the programme through inclusion of their knowledge is a further reason to interact frequently.

We have designed an engagement strategy (Figure. 3) that promptly and communicates scientific results to stakeholders, next users, decision-makers and the public.

One of our first initiatives is activating a web-based end-user hub to disseminate scientific results, documents and news feeds (Figure. 3). Key researchers will succinctly deliver outcomes to stakeholders, institution, regulatory agencies via the website to facilitate dissemination of scientific results and educational material.

Another initial initiative is the set-up of the Advisory Panel, or regulator-industry-iwi (Figure. 3) geothermal "**think-tank**" to consider and provide recommendations on the optimal way to accommodate deep-seated supercritical resource delineation, interconnectivity (between fields), environmental and system management, planning and legal framework considerations for potential future supercritical resource allocation, consenting, utilisation and sustainable system management. A group of representatives from the broad interests in supercritical geothermal ensure all concerns and knowledge to be captured.

2. CONCLUSION

Our multidisciplinary, diverse team leverages longstanding global collaborations to accelerate next generation geothermal energy in New Zealand. Our challenging programme aims to further develop national capability, mentoring emerging expertise and extending top researchers.

Partnering with electricity providers, we will characterise New Zealand's unique geothermal conditions, while drawing on the learnings of supercritical energy exploration worldwide (Japan, Iceland) to identify viable 'deep-heat' systems.

We believe our research will boost regional development, supporting Māori-led geothermal opportunities. Integrating emissions capture, reinjection and/or sequestration simulations in the programme will achieve a step- change in emissions reduction. Emissions capture innovation will also enable new high-value industrial applications, boosting export of low-carbon know-how, and underpinning new industries with high-energy needs (e.g. hydrogen economy).

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