Geothermal The Next Generation: Five years of findings to propose a new exploration phase for New Zealand

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ABSTRACT

After 5 years of research, the Geothermal: the Next Generation team delivered on exploration, understanding, integration of the science, and communication of the challenges facing discovery and exploitation of supercritical geothermal resources. We summarise the findings and new models of the programme that increased and challenged our understanding of the supercritical geothermal possibility for New Zealand. Here, we particularly focus on the exploration part of the programme and propose a new potential phase of geothermal exploration for New Zealand geothermal.

New seismic, magnetic, heat flow and gravity models were produced with a specific focus on the southern part of the central Taupō Volcanic Zone / Te Ahi Tupua. From seismic tomography, we identified a deep large area of partial melt that is the heat source for the Wairakei – Tauhara and Rotokawa geothermal fields. For the first time, we compile geology and geophysics models of these fields. We refined the buried geology underneath the area by proposing a new geological model that better fits observed gravity and magnetic data to constrain the deep stratigraphy likely to be intercepted by deeper drilling. We characterised fracture patterns and orientation and proposed a new understanding of the distribution of basement terranes that are likely to be the reservoir rocks below the current drilled depths. We modelled the hydrothermal fluid circulation around large, deep-seated silicic magma reservoirs and around shallower magmatic heat sources to understand the fluid properties at those conditions. Furthermore, we simulated the magmatic degassing of shallow silicic intrusions to elucidate how hydrothermal convection is affected by magmatic degassing. We ultimately identified where the prime targets are for exploration drilling to develop supercritical resources.

With the government's goal to double renewable electricity generation and achieve this through increased production from renewable, low-carbon energy sources that promote equity and improved socio-economic outcomes for Aotearoa New Zealand, along with wind and solar, geothermal is key to deliver on this vision. With the existing but limited additional conventional geothermal resources, supercritical geothermal and superhot deep enhanced geothermal systems may just be the solution needed.

1. INTRODUCTION

New, Zealand, in common with many countries, is pursuing low-carbon energy security. The vision of 'Electrifying NZ' has multiple complementary objectives, touching on climate change, economic development and core energy policy.

Increasing renewable electricity generation will be extremely difficult to achieve through increased solar, wind and conventional geothermal (Castalia, 2023). Hydroelectricity generation is unlikely to expand beyond the current generation. Additionally solar and wind are weather dependent limiting our energy security and affordability.

However, buried beneath the Taupō Volcanic Zone (TVZ) is the huge potential of superhot geothermal 'supercritical' energy and which could be available 24/7, 365 days a year as a source of baseload electricity generation. In the past 5 years Geothermal: The Next Generation programme has been exploring the potential of supercritical or superhot geothermal. The TVZ has one of the largest heat output in the world allowing us to access this heat/energy on a large scale at shallower depths.

Driven by the now accepted need to decarbonise the energy sector, important new engineering technologies and the need to provide baseload to weather-dependent renewable energy sources, all the major economies are looking at geothermal in a new light.

Based on the science delivered, we were able to demonstrate that supercritical geothermal energy is a long-term economic opportunity for Aotearoa New Zealand. The electric grid modelling suggests that over 2000 MW of carbon-neutral supercritical geothermal electricity could be economically viable for the grid by 2050 (Castallia Limited 2023, Bromley et al., 2024). The programme aimed to identify the locations of future supercritical resources, understand the fundamentals of geochemistry associated with reservoir utilisation, and integrate science for communities (including Iwi groups), regulators, and policy developers.

Here we summarised some of our key geological findings. Our research has refined our understanding of the deep connectivity and heat potential of the southern TVZ, which led to an inventory of New Zealand's supercritical geothermal resources.

2. EXPLORING THE TAUPŌ VOLCANIC ZONE SUPERCRITICAL GEOTHERMAL RESOURCES.

We improved the imaging of the crust. To target potential exploration areas, we refined our understanding of the basement rock and its fracture network; we advanced the understanding of the granitic and magmatic crust, and we advanced the modelling of supercritical fluid location above magmatic intrusion.

2.1 Geophysics

New depth to Curie temperature for Zealandia – implication for heat mapping. Knowledge of the thermal structure of the crust is fundamental for understanding many geologic processes. We analysed a new compilation of magnetic data over central Zealandia continent, including onshore New Zealand, and calculated the depth to base of magnetic sources (DBMS) at regional scale. DBMS often reflects the 580°C isotherm, known as the Curie point temperature. We find complex relationships between DBMS and markers such as the crust and elastic thickness and depth to which earthquakes occur, reflecting a range of processes additional to temperature influence DBMS (Figure 1). We use the depth to base of magnetic sources to generate heat flow models based on the assumption that magnetisation in rocks vanishes at the Curie point temperature (Miller et al., 2023). In the TVZ we image the DMBS isotherm at around 10 km, consistent with the relative locations of the crustal thickness and brittle-ductile transition zone. DBMS is likely shallower than this in localized areas around geothermal fields however we cannot resolve small scale features in our regional scale model.

New 3D magnetotelluric (MT) inversion code "FEMTIC" - The implementation of a new 3D magnetotelluric (MT) inversion code "FEMTIC" provides new insights into geothermal and magmatic systems in New Zealand. Importantly, the new code includes topography and allows for fine meshing around areas of interest, allowing for more realistic models of crustal fluid distribution. This will benefit future work using MT to delineate geothermal systems and will allow for more detailed interpretation of results and refinement of targets for supercritical fluid. The new code was first applied to test on a dataset at Mt Tongariro which has significant topographic relief and refined the model there showing a transcrustal magma plumbing system capped by the hydrothermal system (Heise et al., 2023).

New images of seismic properties in the mid-crust, below geothermal systems - In order to define background seismic properties - the 'habitat' surrounding potential supercritical fluid targets - we have investigated the seismic properties of the mid- crust, below the Wairakei-Rotokawa-Ngatamariki geothermal fields, using seismic wave data from more than 4000 well-recorded local earthquakes. Our seismic tomographic analysis has focused on imaging properties in the 3-8 km depth range (Figure 2), although we can coarsely resolve properties down below 10-km depth. Analysis has highlighted considerable spatial heterogeneity of the properties beneath the region, including volumes of low P-wave velocity in the mid-crust, inferred to represent partial melt – the deep heat sources (Figure 2).

Refined geological models that honour geophysical observations - We have developed new capability to simulate geophysics in particular gravity and magnetics from existing geological models, allowing hypothesis testing where geological models are poorly constrained by drilling. We applied this new method to the geological model of Wairakei-Tauhara-Rotokawa geothermal fields and were able to suggest improvements to the geological model where a poor match to the geophysical data was observed (Figure 3). A new model of the depth to greywacke basement was proposed in areas away from boreholes. This workflow will allow geological model hypothesis testing and illustrates the importance of comprehensive geophysical datasets over geothermal fields. The new method has the potential to better target drilling to test geological hypothesis put forward to improve the match to geophysical observations (Barreto et al., 2024).

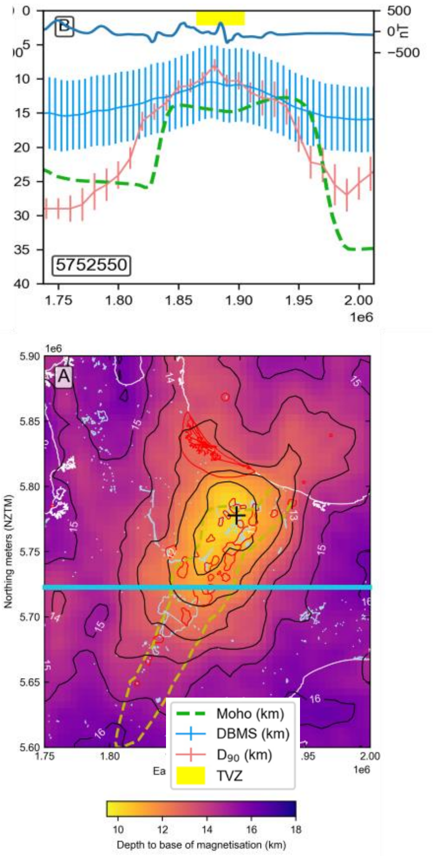

Figure 1: A. Taupō Volcanic Zone depth to base of magnetization MAP estimate. Overlain in red are outlines of geothermal fields. Black cross is the location of the shallowest DBMS (8.9 km). Lakes are shown in light blue and the outline of the modern TVZ is shown as a dashed yellow line. B. DBMS (blue line) with D_{90} estimates (crimson lines) and crustal thickness (green lines) along E-W profile [B] through the TVZ. The yellow bar at the top indicates the TVZ extent. The blue line at the top of each panel is the Total Magnetic Intensity anomaly along the profile. (Miller et al., 2023).

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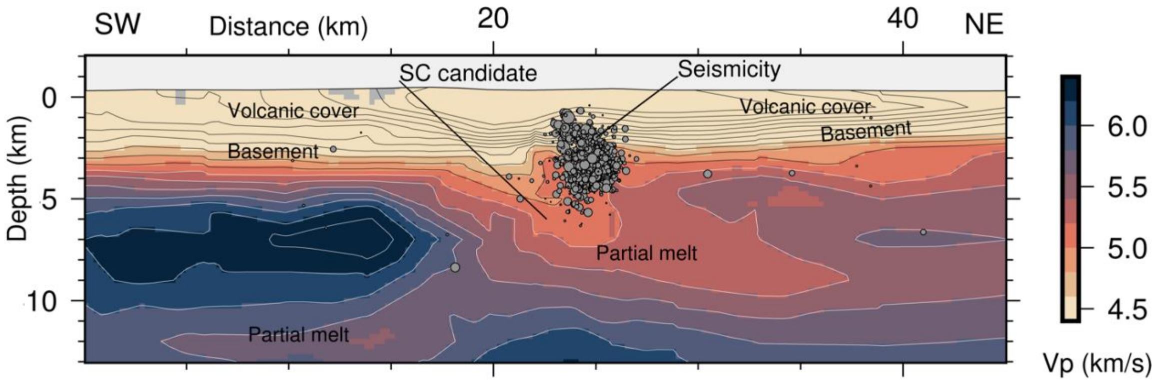

Figure 2: Seismic Vp Cross section underneath a utilized geothermal system in the TVZ. Grey circles are earthquakes (induced and natural). A zone of low velocity is clearly present underneath the geothermal system. We inferred that this is a zone of partial melt that provide heat to the system. We suggest that at ~5 km a potential zone of supercritical fluids could be present.

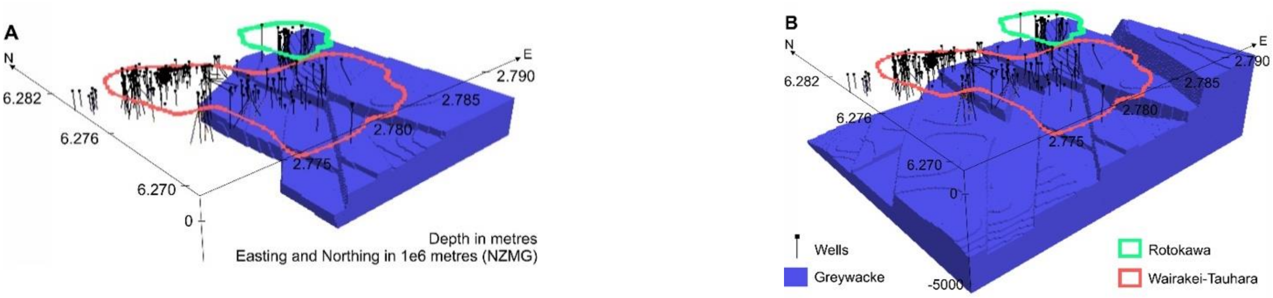

Figure 3: A. Extent of greywacke unit in starting geological model built using only logged geological intervals from wells and fault traces. B. Extent of greywacke unit after application of 3D gravity modelling. (Barretto et al., 2024).

2.2 Geology

New understanding of TVZ basement rocks- Our work undertaken produced a step change in the interpretation of basement terrane geometry under the TVZ. Study of basement rocks brought to the surface in volcanic eruptions(xenoliths) has produced a new interpretation of the distribution of these rocks beneath the TVZ (Mortimer et al. 2023; Figure 4). Figure 4 summarises the new interpretation of terranes (blue and green units) in cross section. The implications for deep geothermal systems and magma genesis are that (1) TVZ structures are not controlled by reactivated steep, crust-penetrating terrane boundaries (black zones in Figure 4); (2) the middle crust under much of TVZ is likely to comprise relatively quartz- and mica-rich Kaweka Terrane instead of Waipapa Terrane. This work provides a useful, 10-100 km scale context for more detailed investigations of TVZ geothermal systems.

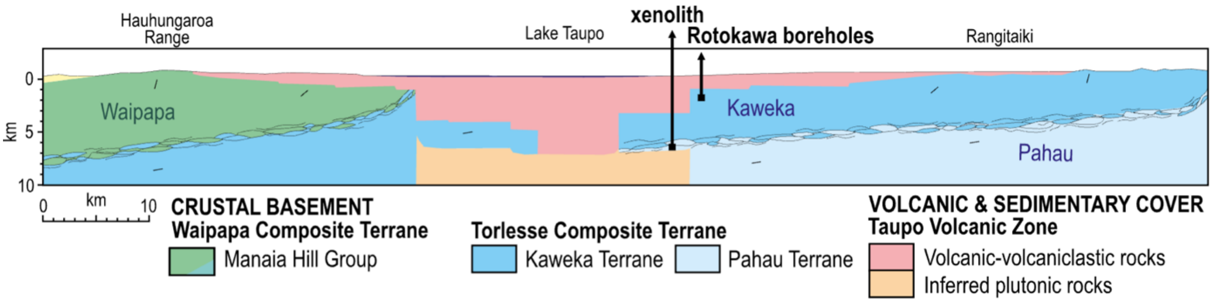

Figure 4: Taupō Volcanic Zone cross sections with the approximate distribution of the basement rocks beneath geothermal fields (no vertical exaggeration) from Mortimer et al. (2023). Modifications of from the 1:250000 scale cross sections from Townsend et al. (2008), Leonard et al. (2010), and Lee et al. (2011). Subsurface sample controls from boreholes, ignimbrite lithics and xenoliths are projected onto the cross sections.

Fracture permeability in the basement rocks – Fracture densities measured in borehole images in the greywacke basement at the Kawerau Geothermal Field (Figure 5) are high enough to yield a fully connected fracture network at reservoir scale, based on fracture network modelling by Kissling and Massiot (2023). The fracture density at borehole scale, and the combination of varied vein orientation and long veins in outcrop suggest that, in a reservoir, some of the veins would be well-oriented for being reactivated in any stress field and could provide connectivity and/or storage for fluids. Increased veining in close vicinity of faults in outcrops suggests a very focused enhanced permeability, as suggested by other studies of greywacke in New Zealand (Figure 6). A multi-scale framework of controls on fractures and fault in greywacke is being developed to aid in selecting key parameters relevant from siting the supercritical borehole to the interpretation of borehole data.

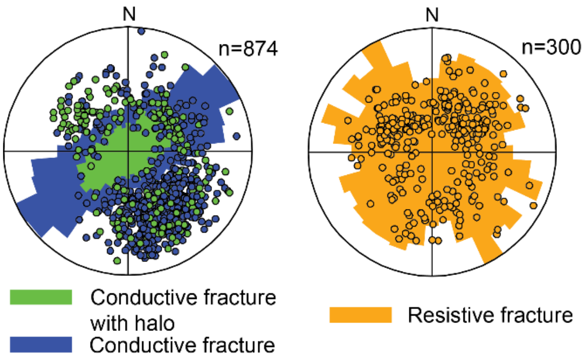

Figure 5: Fracture orientations in a resistivity borehole image from the Kawerau Geothermal Field. Conductive fractures are more likely to be permeable. These are interpreted as mostly representing fractures initiated or reactivated under the current extensional stress field. Resistive fractures are closed and have more varied strike. These are inferred to be dominantly metamorphic in origin. Schmidt projection stereonets, lower hemisphere. n = fracture count

The implication from borehole and outcrop studies is that there will likely be permeable fractures in deep wells drilled into greywacke (Milicich et al. 2024). However, fracture permeability under supercritical pressure and temperature conditions needs to be modelled. In supercritical conditions, fluids need connected fracture networks, but not necessarily fractures of elevated aperture, as fluids have low viscosity. As suggested by laboratory and numerical modelling of granite samples, small cloud-fracture networks may be sufficient to provide sufficient permeability (Watanabe et al., 2019; Liu et al., 2022), though the impact of the anisotropy of greywacke and schists has not been tested yet. Further studies on the effect of stress, metamorphic fabric and hydrothermal alteration are needed to confirm this, in addition to supercritical exploratory drilling.

Figure 6 (next column): Fault displacing meta-mudstone dark-grey bands with intense veining (white) focused within 0.5 m of the fault, in its hangingwall. The fault is perpendicular to foliation. Location: Rarangi, South Island.

Guide to magmatic degassing - The composition of New Zealand's deep magmatic fluids, that drive the TVZ geothermal systems, is relatively unknown. The current conceptual model assumes the deep heat source of hydrothermal fluids is a partial molten zone in the mantle and/or shallow intrusions (~4 km) in the crust. The targeting of deep supercritical or superhot geothermal resources requires knowing: (i) the chemical composition (i.e., the unique fingerprint) of the primary exsolved fluids, and (ii) the spatial distribution of deep-seated magma bodies. Chambefort and Dilles (2023) used rock and clay mineral compositions to track the magmatic fluid signature in geothermal systems using its metal content. We used a 700,000 year-old buried intrusion and its hydrothermal halo at Ngatamariki Geothermal Field as a proxy for what a shallow magma in the crust could looks like. We compared its geochemistry to the rocks and clays of Rotokawa and Ohaaki geothermal fields. Based on these data, over the >20,000-year lifetime of the Ohaaki and Rotokawa geothermal systems, fluids were dominated by chloride-poor meteoric water and contained little magmatic contributions other than conducted heat, some gases (CO_2 - $N_2 \pm H_2S$), and a small fraction of the total H_2O of geothermal waters. Therefore, the inferred magma bodies of intermediate to silicic composition that lie at shallow depth beneath these geothermal systems currently are not, and likely have not been for >20,000 years, degassing significant water and chloride despite the high water and chloride contents of the magmas. By inference, the intermediate to silicic magmas at depth have not transferred large amounts of volatiles to the geothermal systems over this period.

Isotopic evidence for deep fluid circulation – High-temperature (> ~300°C) hydrothermal alteration of rocks by surface-derived waters lowers the rock oxygen isotope ($^{18}O/^{16}O$) ratios, which can be used to track infiltration of water into the crust. Magmas that melt and assimilate these altered rocks can inherit their low $^{18}O/^{16}O$ ratios, providing evidence for hydrothermal circulation down to the depths of magma storage. We analysed the $^{18}O/^{16}O$ ratios (expressed as $\delta^{18}O$ values) of >700 volcanic mineral and glass samples from >90 different TVZ eruptions to look for evidence of these processes in the central TVZ (Rooyakkers et al., 2023a, 2023b). We found that most TVZ magmas have high $\delta^{18}O$ values, consistent with melting and assimilation of high-$\delta^{18}O$ unaltered greywacke basement. However, our geochemical models showed that the observed magma $\delta^{18}O$ values were usually lower than expected, requiring separate assimilation of low-$\delta^{18}O$ altered rocks as well. This mismatch between observed and expected $\delta^{18}O$ values was widespread throughout the TVZ in both time and space, suggesting that high-temperature meteoric-hydrothermal alteration is prevalent around the upper reaches of central TVZ magmatic systems (typically at depths of >5 – 6 km). Our results imply that the magmatic-hydrothermal interface in the TVZ is a dynamic zone where proximity between deep-circulating meteoric fluids and shallow magma bodies leads to large-scale interactions between magmas and altered materials. They also affirm the basis for modelling surface water circulation to magmatic depths in the TVZ to explore where supercritical conditions may be reached.

2.3 Modelling

We have demonstrated the first **source-to-surface models** of the central TVZ hydrothermal system in a 2D setting (Kissling and Ellis, 2023; Kissling et al., 2024). They used these models to investigate the nature of the high-temperature geothermal systems and long-term fluid production and reinjection from them.

The models represent a simplified geological setting with a 20 km-wide continental rift, based on observations from New Zealand's Taupō Rift in the central North Island. This is the target zone for future supercritical and super-hot resource developments, and this model provides fundamental information about the shallow (2 km) locations of geothermal systems and the deeper (10 km) heat sources. They represent deeper magmatic intrusion into the lower crust with a 700°C to 900°C hotplate source at 10 km depth, but considers no other shallow magma bodies. The effective heat flux at the hotplate is 0.77 W/m2. In the model, low-permeability basement-like rocks define the rift margins and basement, which is then covered with volcanic infill. The permeability within the rift decreases with depth in such a way as to match the above-mentioned temperature range, and to respect geophysical constraints, from seismicity and magnetotellurics.

The models produce unsteady, irregular rift-scale hydrothermal circulation in the upper ~5 km of the crust. Plumes of hot water are interpreted as high-temperature geothermal systems, with temperatures of ca. 300°C at 2 km depth. The shallow volcanics control the amount of cool surface water entering the rift scale hydrothermal system. Models with low permeability for the shallow volcanics produce longer lasting and higher temperature geothermal systems, and those with high permeability produce fewer and cooler geothermal systems. Extension of these models to a 3D setting is underway, and has the potential to directly provide estimates of the size of the supercritical resource in the Central TVZ. In addition, the 3D models, once properly calibrated against rift-scale geophysical measurements, have sufficient resolution to inform both long term management and sustainability of fluid extraction from high-temperature geothermal systems.

Furthermore, by including the **crystallizing magmatic heat sources in another set of numerical models**, we studied the temporal evolution of the geothermal systems that form near silicic magma reservoirs. Overall, the efficiency of the heat transfer between the heat source and the circulating hydrothermal fluids is restricted by the relatively low permeability greywacke basement and the presumed low brittle-ductile transition temperature of the silicic host rocks. Under those conditions, deep-seated magma reservoirs produce long-lived (100s kyr), but relatively cool hydrothermal systems (200-250°C at 1 km depth). Small, shallow seated (e.g. at 4 km) intrusions cool on timescales of a few thousand years, but still produce long-lived (10s kyr) hydrothermal systems which are comparably hot (250-300°C at 1 km depth), matching the conditions of the hottest geothermal systems in the TVZ currently active. These simulations also point at the potential presence of regions with supercritical geothermal fluids in the basement above the crystallized magma reservoirs (Figure 7).

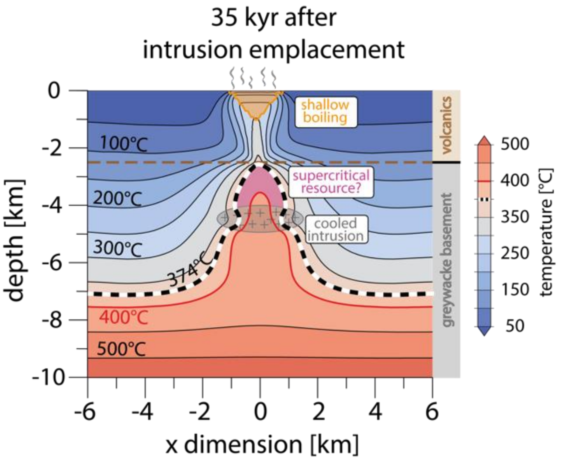

Figure 7: Example of supercritical resource potential above 35,000 years old shallow intrusion.

The modelling also highlights the strong sensitivity of the presence of supercritical fluids at drillable depths to the brittle-ductile transition conditions. This means that future geothermal exploration should consider the mineralogical composition of the host rocks and aim at studying the loss of permeability at these depths as a function of temperature.

Simulations which include exsolution of a magmatic volatile phase from the melt showed that the addition of these fluids to the overlying geothermal systems is strongly hindered by a thick ductile shell around the magma reservoirs. Strong mixing of these magma-derived fluids with meteorically derived fluids diminished the magmatic signature, leading to only minor magmatic fluid fractions at TVZ well depths.

3. FUTURE PATHWAY

Superhot geothermal energy is a potential solution for New Zealand to double its renewable electricity generation within the next 25 years and provide baseload electricity to the system. The Taupō Volcanic Zone (TVZ) is the best location to start the exploratory drilling. Superhot refers to conditions above 400 °C, above the critical temperature of water – hence the term *supercritical*.

Globally, several international projects are underway to push the boundary of knowledge and solve technological challenges that are associated with the drilling and utilisation of deep superhot geothermal resources. New Zealand is a major player in only a very few fields of human endeavour – geothermal is one of them. Just as our predecessors took the calculated risk in the 1950s of funding an exploratory drilling programme and initiating the first large scale geothermal electricity plant using wet steam technology (Wairakei), there is a strong case for leading this next stage of geothermal power development.

In Geothermal: The Next Generation we accumulated scientific evidences and interpretations to support a national strategy for a new phase of government supported exploration campaign for deep geothermal.

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