Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Scientific Drilling in the Taupō Volcanic Zone? Exploring Intense Volcanic and Geothermal Processes in a Rapidly Rifting Arc

Cécile MASSIOT[1], Sarah D. MILICICH[1], Craig MILLER[2], Edward BERTRAND[1], Fabio CARATORI TONTINI[1], Geoff KILGOUR[2], Greg BIGNALL[2], Pilar VILLAMOR[1]

1: GNS Science, 1 Fairway Drive, Avalon, PO Box 30368, Lower Hutt 5040, New Zealand.

2: GNS Science, 114 Karetoto Road, RD4, Taupō 3384, New Zealand.

c.massiot@gns.cri.nz

Keywords: Taupō Volcanic Zone, scientific drilling, continental rift, super-volcano, deep biosphere

ABSTRACT

Scientific drilling programmes yield game-changing datasets to improve knowledge of Earth processes, and are pushing the limits of conventional geothermal uses. The Taupō Volcanic Zone (TVZ) in Aotearoa New Zealand is the ideal place to study the interactions between tectonic, magmatic, volcanic, geothermal and microbiological processes in a rapidly rifting young volcanic arc that hosts numerous rhyolite calderas, andesite and dacite cones. Unravelling the heat and mass transport mechanisms in the TVZ has direct implications for understanding the entire "subduction factories", better assess associated earthquake and volcanic hazards, and sustainably use geothermal resources which, in New Zealand, are of great significance to Māori.

Since the 1950s, extensive geophysical, geological and geochemical datasets have been collected throughout the TVZ. Geothermal drilling up to 3.2 km depth and 340°C into near-neutral pH reservoirs has provided a window into the sub-surface TVZ. This lead to discoveries on geothermal, continental rift and arc systems. To expand the exploration of TVZ's subsurface with *in-situ* data outside conventional geothermal reservoirs, we propose the establishment of a scientific drilling programme. Scientific drilling will advance our understanding of: (1) feedbacks between the volcanic arc and an active rift; (2) controls on the timing and rates of volcanic and seismic events; (3) large-scale hydrology and magma systems; and (4) the microbiological diversity and function of the deep biosphere. We present the Okataina Volcanic Center, an accessible rhyolitic caldera where extensive surface data is already available, as one of the candidate areas with exciting potential to answer these research themes. At these very early stages, we seek to build strong relationships with Māori groups, and a multi-disciplinary national and international team, to develop the idea of a TVZ scientific drilling. This programme will aim to test fundamental geoscientific and geothermal concepts within the TVZ's exceptional geological setting, and strengthen linkages with other ongoing geothermal scientific drilling programmes.

1. INTRODUCTION

Scientific drilling and associated studies in volcanic and geothermal regions have significantly improved our understanding geological processes (including the Iceland Deep Drilling Project (IDDP): Elders et al., 2014; Fridleifsson et al., 2018; Campi Flegrei: Carlino et al., 2015; Unzen Scientific Drilling Project: Nakada et al., 2005; and Brothers Volcano in the Kermadec Arc, the first active submarine volcano to be explored by scientific drilling: De Ronde et al., 2019). For example, the first phase of IDDP yielded the world's hottest well during flow test, which advanced concepts of hydrothermal and plate tectonics in mid-ocean ridge settings (Elders et al., 2014; part of a special issue of the *Geothermics* journal). IDDP-1 also improved the magmatic and conceptual model of the Krafla Geothermal Field and magma plumbing beneath collapse calderas (e.g., Kennedy et al., 2018) alongside drilling, downhole measurements and geophysical technology advancement (Asmundsson et al., 2014; Palsson et al., 2014) which are increasingly used in conventional geothermal drilling. The second phase of IDDP at Reykjanes successfully drilled into a supercritical geothermal system and provides opportunities to investigate water-rock interaction in the active roots of an analog of a submarine hydrothermal system (Fridleifsson et al., 2018). The Long Valley exploratory well provided data on the Long Valley caldera structure and evolution (Rundle and Eichelberger, 1989), including downhole stress measurements (Moos and Zoback, 1993) from the, then recently developed, ultrasonic borehole televiewer (Zemanek et al., 1970). Borehole televiewer logs are increasingly used in geothermal fields to map fractures and in-situ stress, which also inform on plate tectonic processes (e.g., Ziegler et al., 2016). In intra-arc rifts such as Kyushu, Japan (Kamata and Kodoma, 1999), and the Trans-Mexican Volcanic Belt (Ferrari et al., 2012), which host a large geothermal potential (Bertani et al., 2016), it is important to pursue efforts to better understand magmatic and tectonic processes, and the role of the subducted slab in fluid chemistry and circulations through the crust.

The Taupō Volcanic Zone (TVZ; Figure 1), New Zealand, is a young (<2 My) rifted volcanic arc where active continental rifting and subduction processes yield one of the world's most productive areas of Quaternary silicic volcanism (at least 6000 km^3 of magma; Wilson et al., 1995; Wilson et al., 2009), with fast rift evolution and fault slip rates (Litchfield et al., 2014; Villamor et al., 2017), high heat flux (average of 700 mW/m^3; Bibby et al., 1995), numerous geothermal manifestations (Wilson and Rowland, 2016, and references therein) and a wide microbial fauna (Power et al., 2018). Seven decades of research and geothermal development in the TVZ makes it a world-class natural laboratory to study relationships between faulting, heat transfer, fluid circulations and water-rock interactions, stress and strain rate, volcanic structures and caldera margins, and the biosphere.

The TVZ is a populated area which significantly contributes to the country's economy through geothermal electricity production (18% of the total national generation), direct geothermal use and tourism (Ministry of Business, Innovation and Employment, 2018). The geothermal resource is a taonga (treasure) of great significance to Te Arawa Māori people. Te Arawa have for generations regarded the geothermal resource as a gift from the Atua, and call it Waiariki, water of the gods. Māori groups use geothermal resources both historically and contemporarily, and the landscape and geothermal manifestations are key parts of their cultural and traditional knowledge. As the world transitions to a low-carbon economy, it becomes even more important to study geothermal processes to be able to harness it sustainably, especially in silicic regions which compose large parts of the continental crust.

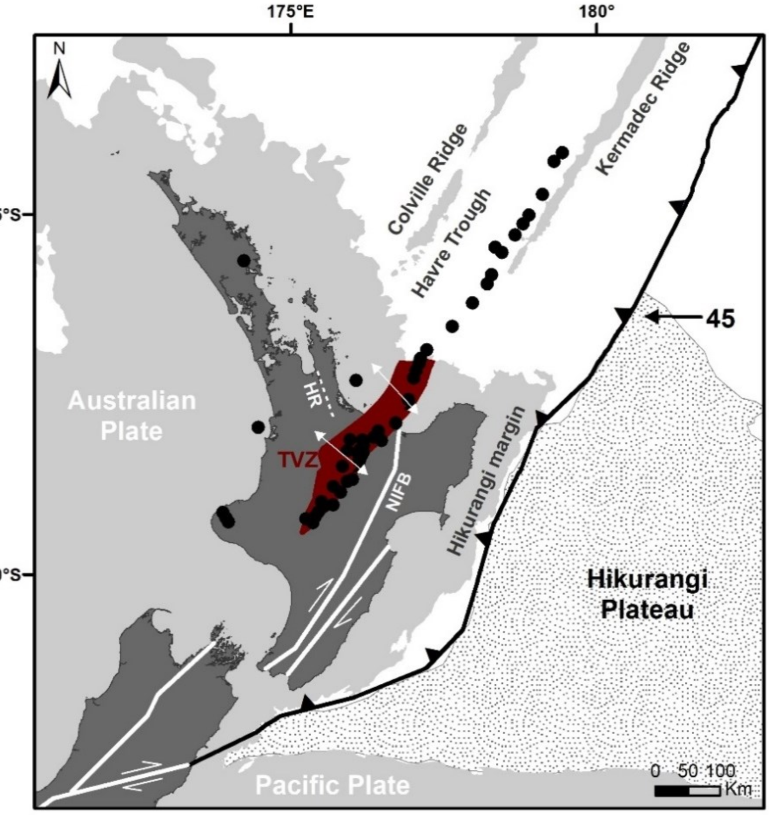

Figure 1: Tectonic settings of the northern New Zealand and TVZ (red shading), with recent volcanism (<1 Ma; black circles; Seebeck et al., 2014a); geodetic vectors of extension (double arrows; Wallace et al., 2004) and relative plate motion (single arrow; DeMets et al., 1994) in mm/year. HR=Hauraki Rift; NIFB=North Island Fault Belt.

The TVZ is subject to seismic (Anderson and Webb, 1989; Sherburn et al., 2000) and volcanic risks, including from Taupō and Okataina caldera volcanoes (Barker et al., 2019), which are continuously monitored (Miller and Jolly, 2014). A global analysis by the European Science Foundation calculated the benefits of understanding and monitoring supervolcanoes such as Taupō as US$0.5–3.5 B pa, and a large eruption in the TVZ would have strong repercussions in New Zealand and larger part of the world (Plag et al., 2015).

The study of microbial community composition and diversity within defined ecosystems has substantial conservation, scientific, and indigenous cultural value. Cross-disciplinary ecosystem surveys such as those undertaken by the 1000 Springs Project (Power et al., 2018) identify not only new microbial taxa, but also contribute knowledge on microbial community assembly, geobiological interactions and ecological services provided by these ecosystems. Social benefits also flow through increased knowledge in general public and indigenous communities, and provide an ability to resource development with conservation. A scientific drilling programme in the TVZ will offer similar opportunities. The deep biosphere is estimated to support ~55-85% of the total global prokaryotic (bacteria and archaea) and up to 10% of the total global biomass (Whitman et al., 1998; McMahon and Parnell, 2014). This represents on the order of 10-100 fg of biomass or $5.4\times10^{29-30}$ cells (McMahon and Parnell, 2014; Parkes et al., 2014). Yet as a scientific community, we know virtually nothing about the microbial community diversity, function, activity or ecosystem services this ecosystem provides (Wilkins et al., 2014; Colman et al., 2017).

Numerous groundwater and geothermal drillholes in the TVZ yield invaluable geo-scientific data and pushed the understanding of the functioning of the TVZ. However, the objectives of these drilling campaigns to date are usually driven by economic considerations rather than scientific data collection, especially beyond the initial exploration phase. Scientific drilling offers multiple opportunities for sampling (rocks and fluids), *in-situ* measurements (multi-parameter downhole and stress measurements), and long-term monitoring (e.g., seismicity, temperature, fluid chemistry, microbiology). In addition, although many boreholes have been drilled in the TVZ, those >100 m deep are mostly confined to geothermal fields for energy generation, themselves usually <3 km depth. A scientific drilling in the TVZ will offer new opportunities to investigate and monitor geological regions yet unexplored, spatially and/or with depth.

A scientific drilling and borehole monitoring programme in the TVZ will provide a high-resolution geological record to help constrain the timing, rates and interactions between processes that involve heat, magma, fluids and structure. Sampling and monitoring will also improve the geological interpretation of geophysical signals conventionally used for geothermal resource assessment, which will then be transferable to other geothermal and volcanic regions, e.g., by relating magnetotelluric results to the presence of fluids and/or magmas. These high-level processes and techniques are key to locate and evaluate the present state of magmas and fluids, which are parameters necessary to improve the delineation and sustainable use of geothermal resources; and faulting and volcano hazard assessments. A scientific drilling programme will also promote outreach to local communities, multi-disciplinary pre- and postdrilling surveys, with international collaborations, including with other ongoing and planned programmes in geothermal and volcanic regions (e.g., Iceland Deep Drilling Program, Friðleifsson et al., 2018; GemEx, Jolie et al., 2018; Newberry Deep Drilling Project; Japan Beyond-Brittle Project).

In this paper, we present the geological settings of the TVZ, the wide range of available data, and some of the themes that can be addressed by a scientific drilling programme in this region. It is important to note that we are in the process of refining the scope and research questions down to a few key options. The location and target depth will be selected to best answer the research questions as well as societal and indigenous Iwi/ Māori interests following extensive consultation, with consideration of engineering requirements. Indeed, some potential targets would require challenging drilling in corrosive high-temperature environments, while other colder regions would allow for conventional drilling and more extensive coring, downhole measurements and monitoring. At this early planning stage, we are in the process of engaging with Iwi/ Māori, refining the concept of a TVZ scientific drilling programme and increase linkages with other ongoing drilling programmes in geothermal and volcanic areas.

2. TVZ: A NATURAL LABORATORY FOR ARC VOLCANISM, RIFTING AND GEOTHERMAL PROCESSES

2.1 Geological Context

The TVZ represents the southernmost ~300 km-long portion of the ~2800-km-long Tonga-Kermadec arc system where it intersects and terminates in the North Island, within the continental crust of Zealandia (Figure 1; Cole and Lewis, 1981; Parson and Wright, 1996; Mortimer, 2004; Smith and Price, 2006). Within a ~120 × 60 km central segment of the TVZ, rhyolitic volcanism related to the subduction of the Pacific Plate under the Australian Plate is exceptionally frequent and voluminous (Wilson et al., 1984; Wilson et al., 2010; Wilson and Rowland, 2016, and references therein). This central segment hosts a very active hydrothermal province with heat and eruption volume outputs similar to those of Yellowstone (Christiansen, 2001; Hurwitz and Lowenstern, 2014).

The TVZ has an intensely faulted thinned crust (~15-25 km thick; Stern, 1987) hosting the Taupō Rift, an active continental rift rapidly widening with extension rates ranging from <5 mm/year south of Lake Taupo to about 15 mm/year at the Bay of Plenty coastline (Wallace et al., 2004; Lamb, 2011; Villamor et al., 2001, 2017). Over its short ~2 Myr history, the Taupō Rift has rapidly narrowed and propagated southwards along its axis ~70 km in 350 kyr (Wilson et al., 1995; Parson and Wright, 1996; Villamor et al., 2017). The segmented nature of the Taupō Rift potentially relates to deeper inherited basement structures (Rowland and Sibson, 2001). Some of these extend well beyond the TVZ, such as NW–SE orientated structures related to the Hauraki Rift; and N-S related to the North Island Fault Belt that may influence fluid flow into the roots of the geothermal systems (Rowland and Sibson, 2004).

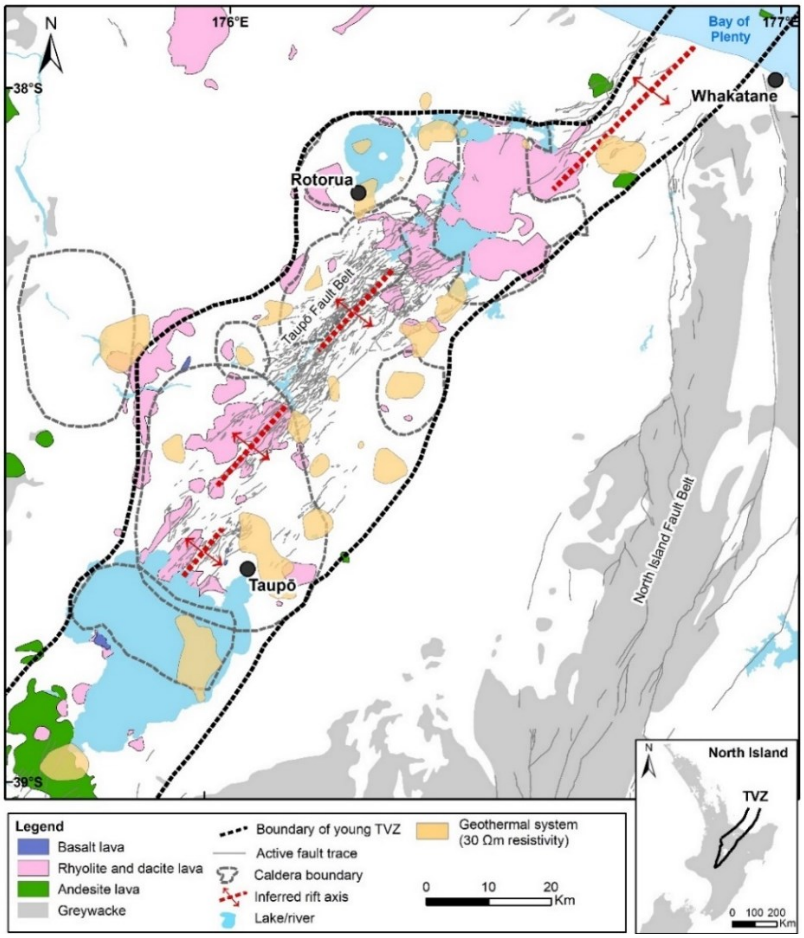

Figure 2: Tectonic and volcanic settings of the TVZ showing simplified geology (Leonard et al., 2010), the locations of the geothermal systems as defined by anomalously low electrical resistivity (<25 Ωm: Bibby et al., 1995), the boundary of the young (350 ka-present) TVZ and caldera locations (Wilson et al., 1984, 2009) and Taupō rift axis (Rowland and Sibson, 2001). Active faults are from the GNS active fault database (GNS Science Active Fault Database, 2020).

In the central TVZ, there are complex inter-relationships between volcanism, magmatism, tectonism and fluid flow (e.g., Ellis et al., 2007; Allan et al., 2012; Rowland and Simmons, 2012; Dempsey et al., 2013, Seebeck et al., 2014b; Barker et al., 2016). Voluminous volcanic eruptions coincide in time and space with stages of evolution of the Taupō Rift by weakening the crust and localising deformation (Villamor et al., 2017a). Volcano-tectonic interactions have been documented for some fault ruptures (Villamor et al., 2011). Numerical flow models also show that surface outflows from faults are strongly controlled by the combination of fault permeability, fault system architecture and the location of the heat source with respect to the faults (Kissling et al., 2018), yielding a complex configuration for evaluating structural geothermal potential.

The TVZ is a young and dynamic arc which evolves significantly faster than comparative intracontinental rifts such as the African Rifts (Corti, 2009; Villamor et al., 2017). The TVZ is also a unique place to study the transition between the rifted arc (continental crust) and the backarc extension offshore along the Kermadec Arc (oceanic crust) (Parson and Wright, 1996). Further exploring the volcanic stratigraphy by drilling, combined with the geochemical analysis of the eruption deposits, will allow to study the effects of variations in subducted material through time, i.e., between the Hikurangi plateau and the oceanic crust of the Pacific Plate (Timm et al., 2014).

Installed geothermal electricity generation of 1 GWe makes New Zealand one of the top 10 countries in the world in installed geothermal capacity, and one of the highest in percentage of electricity, with further resources delineated for future use, and additional ones protected. There is also interest in high-value minerals, either directly extracted from the geothermal brine, or as a precursor analogue to epithermal deposit as those located further north in the Coromandel Volcanic Centre, an ancestor of the TVZ (Simmons et al., 2016; Hamilton et al., 2018). Understanding the TVZ-scale hydrological system is thus key to discover and sustainably use resources while protecting culturally and economically important features.

2.2 70 years of Geothermal Research and Drilling

The TVZ has long been an international focus of research and geothermal resource development, beginning with the exploration of the Wairakei Geothermal Field in the 1950’s (Grindley, 1965; White and Chambefort, 2016, and references therein). Extensive geological and biological datasets have been collected throughout the years, with public funding and through collaboration with the geothermal industry, yielding a multi-scale, multi-parameter view and conceptual model of the TVZ. The research programmes currently underway demonstrate the strong interest by New Zealand government agencies and the collaborative desire of the research community to unravel the complex processes occurring in the TVZ, from blue sky research to resource and geological hazard evaluation, microbiological investigations and community engagement.

Early DC-resistivity surveys have promoted discoveries of geothermal fields (Bibby et al., 1995), and this technique is now expanded to the third dimension with magnetotelluric (MT) surveys (e.g., Heise et al., 2010; Bertrand et al., 2015). The high electrical resistivity contrast between high-resistivity fresh volcaniclastics, and low-resistivity (conductive) fluids and altered clays, enables tracking large-scale loci of hot fluids and hydrothermally altered rock. Resistivity thus became a fundamental geothermal exploration technique, especially as the rocks are strongly attenuating seismic signals which limits the efficiency of active seismic surveys commonly used in sedimentary basins. Large-scale MT surveys in the TVZ demonstrated the presence of conductive plumes, rising from the brittle-ductile transition to surface. These plumes provide great potential for future exploration of deep geothermal resources and for the understanding the deep sources of geothermal systems (Bertrand et al., 2012, 2013, 2015). The first MT survey in lakes were conducted in 2018. Ongoing geophysical surveys focused in the lakes at the boundary of the Okataina Volcanic Centre caldera have shown that these lakes could have a significant geothermal potential. For example, the total conductive thermal output of Lake Rotomahana alone, estimated from heat flow survey and lake calorimetry, is > 100 MW, with a mean heat-flow of ~ 6 MW/m^2 (Tivey, et al., 2016).

During the exploration and development of the geothermal fields for electricity and direct use, numerous wells have been drilled to depths of up to 3.2 km. Petrographic analysis of cuttings and cores from these wells provided a subsurface record of many geologic events not present at surface in this rapidly subsiding and infilling rift. For example, drilling has revealed buried andesite volcanoes that existed prior to the eruption and emplacement of thick ignimbrite and tephra units (e.g., Grindley, 1965, Milicich et al., 2013b; Chambefort et al., 2014). These drilling samples have also allowed to determine the progression of andesite magma along the arc and establish the variation in magma production rates through time (Browne et al., 1992). Recent zircon U-Pb dating has refined this stratigraphic record in many of the geothermal fields, provided constrained timing on both local and regional magmatic and volcanic events, and rates of faulting and rifting affecting those areas (Wilson et al., 2008, 2010; Milicich et al., 2013a; Eastwood et al., 2013; Chambefort et al., 2014; Rosenberg, 2017).

Fundamental techniques for identifying permeable zones in geothermal boreholes, including from temperature, pressure and fluid velocity (spinner) logs have been developed in the TVZ (e.g., Grant and Bixley, 2011; Zarrouk and McLean, 2019). In addition, acquisition of downhole image logs since 2010 has yielded the first *in-situ* observations of fracture networks and contemporary stress directions in boreholes. They revealed a broad agreement with the fault mapping in surface and subsurface using stratigraphic offsets, but with local variations interpreted to relate to nearby active faults, primary fracturing pre-dating the rift, and regional plate motion (Villamor et al., 2017b and references therein; McNamara et al., 2019). Borehole imaging now provide constraints on fracture modes of formation and distribution throughout the reservoirs (Massiot et al., 2017), which can be used to model reservoir-scale pervasive fracture permeability and behavior under stress (Kissling et al., 2015; Kissling and Massiot, 2020). Rock physics studies of geothermal drill-cores provided much-needed data on the mechanical and permeability behavior of the volcanic host rocks, to help with reservoir stimulation and management (Siratovich et al., 2014; Wyering et al., 2017; Cant et al., 2018). Detailed analysis of facies on image logs also revealed stratigraphic variations to a scale that was not possible with cuttings only, with implications for the volcanic history of the TVZ and geothermal reservoir characterisation (Massiot et al., 2015; Milicich et al., 2020).

The geothermal knowledge and expertise developed since the 1950’s in the TVZ has pioneered geothermal sciences with close linkages to earthquake and volcano research. However, fundamental questions about the inner functioning of the rifting arc and how they relate to geothermal systems remain unanswered.

3. FUNDAMENTAL RESEARCH QUESTIONS THAT CAN BE ADDRESSED IN THE TVZ

We have identified four themes of global relevance that a scientific drilling programme in the TVZ will contribute to. Each of these themes can be beneficial at cultural, economic (including geothermal energy), and hazard levels. In this section, we present these themes and highlight examples of how advancing these questions would help the sustainable development of geothermal energy.

3.1 What are the feedbacks between magmatism and tectonism?

The TVZ has clear examples of feedback between tectonism and magmatism at various scales. For example, the Taupō Rift evolution has been suggested to be aided by the occurrence of large silicic eruptions (Villamor et al., 2017a). The 27 ka Oruanui supereruption of the Taupō caldera (530 km^3 magma) is suggested to have been triggered by a rift-related tectonic event allowing rupturing of shallow magma chambers and lateral magma transport, without necessarily leaving any discernible geological imprint (Allan et al., 2012). Downhole image logs collected so far within geothermal boreholes show that fractures and stress directions are dominantly related to the rift extension, with local variations attributed to nearby active faults (McNamara et al., 2015; Villamor et al., 2017b and references therein). However, no structural or stress data has been published to date from boreholes close to caldera margins, and the effects of potential deep magma chambers on fracture systems at the shallower depths of geothermal reservoirs remains poorly constrained. Better understanding these feedbacks is thus important for geothermal systems, to identify heat sources and structural pathways for hot fluids. Research questions related to this theme include:

- Chicken or egg: do structures control locations of magma and fluid transport or do structures respond to magma pulses?
- How are stresses, structures and fluid flow controlled by the geometry of faults, calderas, and their intersections?

3.2 What controls the timing and rates of deformation, volcanic eruptions and earthquakes?

With infilling of such an active rift with volcanic and sedimentary deposits, geological samples from geothermal wells, combined with surface studies of recent deposits, provides good record of eruptive and tectonic activity. Increasing evidence shows that large silicic magmas can be transformed from crystal mush zones to eruptible magma in decades to centuries, potentially driven by internal (magma) and external (tectonic) processes (Allan et al., 2013). A major unknown in our understanding of large rhyolitic magma reservoirs is the thermal state of the crust. High silica rhyolites are very sensitive to small temperature changes, which are modulated by the thermal conductivity of the crust (Gualda et al., 2012). This could be the key to converting very large volume crystal mush zones to eruptible magma over relatively short timescales. Despite significant landscape and magma disruption caused by large eruptions, some geothermal systems have been shown to be stable, suggesting that the life of geothermal systems is mainly controlled by deep-rooted sources of heat (Rowland and Sibson, 2004; Milicich et al., 2013b; Chambefort et al., 2014). This implies that some major fluid pathways are constant through time. Investigations into the history and location of silica sinters also suggests that geothermal systems have a finite lifetime with pulses of activity, although it is not known what the underlying controls are (Loame et al., 2019). Advancing knowledge of these timing is fundamental to quantify the long-term sustainability of geothermal systems. Research questions related to this theme include:

- How can large silicic volcanism be produced and sustained for ~2 Myr?
- What is the thermal state of the crust and how does this modulate the eruptibility of rhyolitic magmas?
- What drives earthquake swarms, volcanic unrests and transient geodetic anomalies?
- What is the present magmatic state of the calderas?
- How do hydrothermal systems change through time and how are they affected by large eruptions? Are the controls on geothermal systems' lifetimes different in arc/subduction zones compared to mid-ocean ridges?

3.3 Large-scale hydrology and magma systems: how are fluids and heat conducted through a continental rifted arc?

The combination of subduction and rifting causes the crust to thin, allowing mantle upwelling, high magma production rates and a very high heat flux (Bibby et al., 1995; Wilson et al., 2009). Rising conductive "plumes" imaged by MT beneath most of the geothermal fields represent zones of partial melt and saline brines, but some plumes do not have hydrothermal surface expression or are offset compared to surface expression (Bertrand et al., 2013). Identifying zones hosting supercritical fluids (>374°C and 22 MPa for pure water), is being considered increasingly important worldwide to use higher enthalpy fluids with potentially reduced surface footprint (Reinsch et al., 2017). Experimental studies of granitic rocks at 350-500°C show that permeability could also be sustained at the brittle-ductile transition in silicic rocks (Watanabe et al., 2017). Conversely, identifying recharge zones where cold meteoric fluids go down into the crust is important to understand the TVZ convection system (Kissling and Weir, 2005), and for managing geothermal fields. Small magma bodies remain difficult to detect, but may yield very powerful geothermal wells (e.g., the Iceland Deep Drilling Project phase 1; Elders et al., 2014). Hence, better understanding large-scale hydrology and magma systems are important to constrain the state of the crust and its effects on faulting and volcanism, and to delineate geothermal resources. It is also important for evaluating potential deep connectivity between geothermal fields, and the natural rates of recharge of geothermal reservoirs. Research questions related to this theme include:

- Are ductile rocks permeable?
- Are shallow intrusions common? Are there supercritical reservoirs in silicic rocks? Can they be imaged using geophysical methods?
- Are geothermal field's roots connected at depth?
- Is high permeability generally found at caldera margins, concentrated faulting with high strain rate, or within deep faults rooted in the basement? What defines the locations of discharge (geothermal systems) and recharge?

3.4 Does the geological and geochemical context of the TVZ support a deep biosphere microbiological community?

The deep hot biosphere (Gold, 1992; Colman et al., 2018) represents a massive reservoir of microbial taxonomic and physiological diversity. Based upon the current temperature limit of life, microorganisms should be viable in the shallow crust up to a temperature of ~122°C. Despite the size, the activity of deep subsurface microbial populations, and therefore their relative importance is considered negligible due to their substantially slow growth rates compared to those of near-surface or subaerial ecosystems; initial estimates of microbial growth in deep marine sediments claim doubling times in the order of an unbelievably slow 100's-1,000's of years (Jorgensen and D'Hondt, 2006). These are difficult to comprehend (even believe) when compared to growth rates at the near-surface, and often negatively influences the perceived importance of this ecosystem. The often-cited reason for the lack of microbial activity is insufficient access to micronutrients and/or appropriate redox-paired substrates to permit cell growth or even survival (Jorgensen and D'Hondt, 2006; Onstott, 2016). Taken together, this presents a quandary that has yet to be solved by the scientific community: *How do the observed slow growth rates and the apparent lack of microbially-available substrates in the deep biosphere support what represents the largest and most diverse reservoir of prokaryotes on this planet?*

This 'cool' maximal temperatures able to support microbial life obviously limits any biology-focused investigation to "shallow" or cooler components of any scientific drilling programme. Nevertheless, possible questions that could be addressed by a focused scientific drill could include:

- The determination of the physicochemical drivers that promote microbial community assembly and diversity.
- The development of a greater understanding of the microbial growth rates and responsiveness within the extremely nutrient/substrate poor deep subsurface.
- To test whether microbial community composition and/or geochemical fluid composition varies with tectonic activity.
- To develop methodology to capture microbial responses to changes deep subsurface ecosystem conditions.

The outcomes of this research could substantially clarify the way we think about the subsurface metabolic energy landscape, subsurface fault geochemistry and mineralogy, the dispersal of microorganisms, and the extent of microbial activity and diversity in the deep biosphere. Understanding the biogeochemical interactions has the potential to improve modelling and understanding of ecosystem services provided by subsurface microbial communities (Long et al., 2016). It also has implications for astrobiology, providing mechanisms for microbial survival and growth in energy-limited extraterrestrial environments, particularly where plate tectonics are observed (e.g., Europa; Kattenhorn and Prockter, 2014). Additionally, this study will increase the known taxonomic diversity of the deep subsurface through the discovery and cultivation of new microbial strains (despite the size of the deep biosphere, only 8% of the known microbial strains are derived from deep subsurface environments (Schloss et al., 2016). To highlight this potential, we cite a recent study of a groundwater aquifer, where researchers reconstructed >2,500 near complete microbial genomes representing the majority of known bacterial phyla and discovered, remarkably, an additional 47 new phylum–level taxonomic lineages (Anantharaman et al., 2016).

4. EXAMPLE OF A REGION WITH POTENTIAL DRILLING TARGETS: THE OKATAINA VOLCANIC CENTRE

Several general locations lend themselves to tackle several of the above-listed research questions, although the specific location, and even region, of a scientific drillhole will be decided as the planning advances. Here, we present the Okataina Volcanic Centre as one of the regions that has a good potential to answer some of the questions listed in Section 3.

The Okataina Volcanic Center (OVC; Figure 3a) is a caldera complex located between (1) Rotorua, where geothermal is used for heating, bathing and tourism (White and Chambefort, 2016); and (2) the Kawerau Geothermal Field which has ~140 MWe of installed capacity and significant direct geothermal use (Figure 3). This region and its hydrothermal manifestations are of high cultural importance to Māori who were the first inhabitants of Aotearoa. The ~AD1315 "Kaharoa" rhyolite magmatic eruptions from Tarawera volcano vents (Nairn et al., 2005) is an important marker horizon for dating pre-European arrival to New Zealand, thought to be in the late 13th century. The Pink and White Terraces, now thought to be drowned in Lake Rotomahana following the 1886 AD Tarawera eruption (de Ronde et al., 2016), were already a world-class tourism destination in the 19th century.

At least two periods of collapse accompanied voluminous ignimbrite at ~350 ka (> 160 km^3) and ~61 ka (> 100 km^3; Downs et al., 2014; Cole et al., 2014, and references therein). Rhyolite dome extrusion and explosive tephra eruptions have occurred throughout the history of OVC. In the last 50 kyrs, there have been at least 23 silicic episodes from OVC, with an average eruption rate of ~14.9 km^3 (magma volume) every kiloyear (Smith et al., 2005). Basalts have been intruded into the rhyolitic reservoir beneath the OVC, likely facilitated by rapid rift extension rates (Rowland and Sibson, 2001, Smith et al., 2005). Some basalts have reached the surface, for example during the 1315 and 1886 AD fissure eruptions from Tarawera volcano (Nairn et al., 1981, 2005; Seebeck et al., 2009; Cole et al., 2010). Geochronology at the nearby Waiotapu and Kawerau geothermal fields constrain the ages of older stratigraphy and, at Kawerau, provide evidence of early strike-slip faulting in the Mesozoic basement and influence of inherited structures perpendicular to the modern rift (Wilson et al., 2010; Milicich et al., 2013a; Milicich et al., 2013b).

The caldera is located at a major offset within the Taupō Rift and represents a structurally complex transfer zone where fault orientation differs from the overall NE-SW dominant strike, suggesting significant stress changes in this area (Rowland and Sibson, 2004, Seebeck et al., 2010). Borehole image interpretations show that the change of direction of main extension direction continues in the sub-surface, with the dominant fracture strike and maximum horizontal stress (S_{Hmax}) azimuth being NE-SW to the south of the OVC in the Rotokawa and Wairakei Geothermal Fields (Villamor et al., 2017b and references therein; McNamara et al., 2019); and ENE-WSW to the north-east of the TVZ at the Kawerau Geothermal Field (Wallis et al., 2012). This change in rift axis orientation is potentially due to the presence of partial melt thermally weakening the crust (Ellis et al., 2014).

Extensive geological and geophysical datasets have already been collected, including geological and active fault mapping (Nairn, 2002; Leonard et al., 2010; Langridge et al., 2016), stratigraphy and magmatic processes (e.g., Smith et al., 2005). Paleoseismology shows that some of the fault ruptures are associated with volcanic eruptions (Villamor et al., 2011). MT inversions show low-resistivity plumes under Rotorua and Waimangu, associated with hydrothermal surface features (Heise et al., 2016; Figure 3b). Several geothermal fields have been identified near the caldera margins from DC-resistivity and MT (Bibby et al., 1995; Hurst et al., 2016, and references therein; Heise et al., 2016). Ongoing geophysical investigations in the lakes highlight the important geothermal potential (Tiveyet al., 2016) in the area in its relation to the large-scale structural and volcanic setting of the OVC (Caratori Tontini et al., 2016), showing that hydrothermal upflow zones are strongly controlled by the structural lineaments controlling the development of the OVC.

The OVC is therefore be an ideal region to test hypotheses related to the feedback mechanisms between the arc and the rift, the relative importance of large partial melt bodies and inherited structures in the segmentation of the rift, stress and fracture interactions between the rift and the caldera margins, how it impacts the hydrology of the TVZ, and the geological nature of the conductive MT plumes. Borehole monitoring there has the potential to provide near-real time measurements of temperature and fluid flow modulated by earthquakes or magma pulses. Elucidating the controls on the arrest of faults and dikes (such as the northern end of the dike of the 1886 AD Tarawera eruption), and hence the potential magnitude of earthquakes and potential link with volcanic eruptions, is important for earthquake and volcanic hazards evaluation.

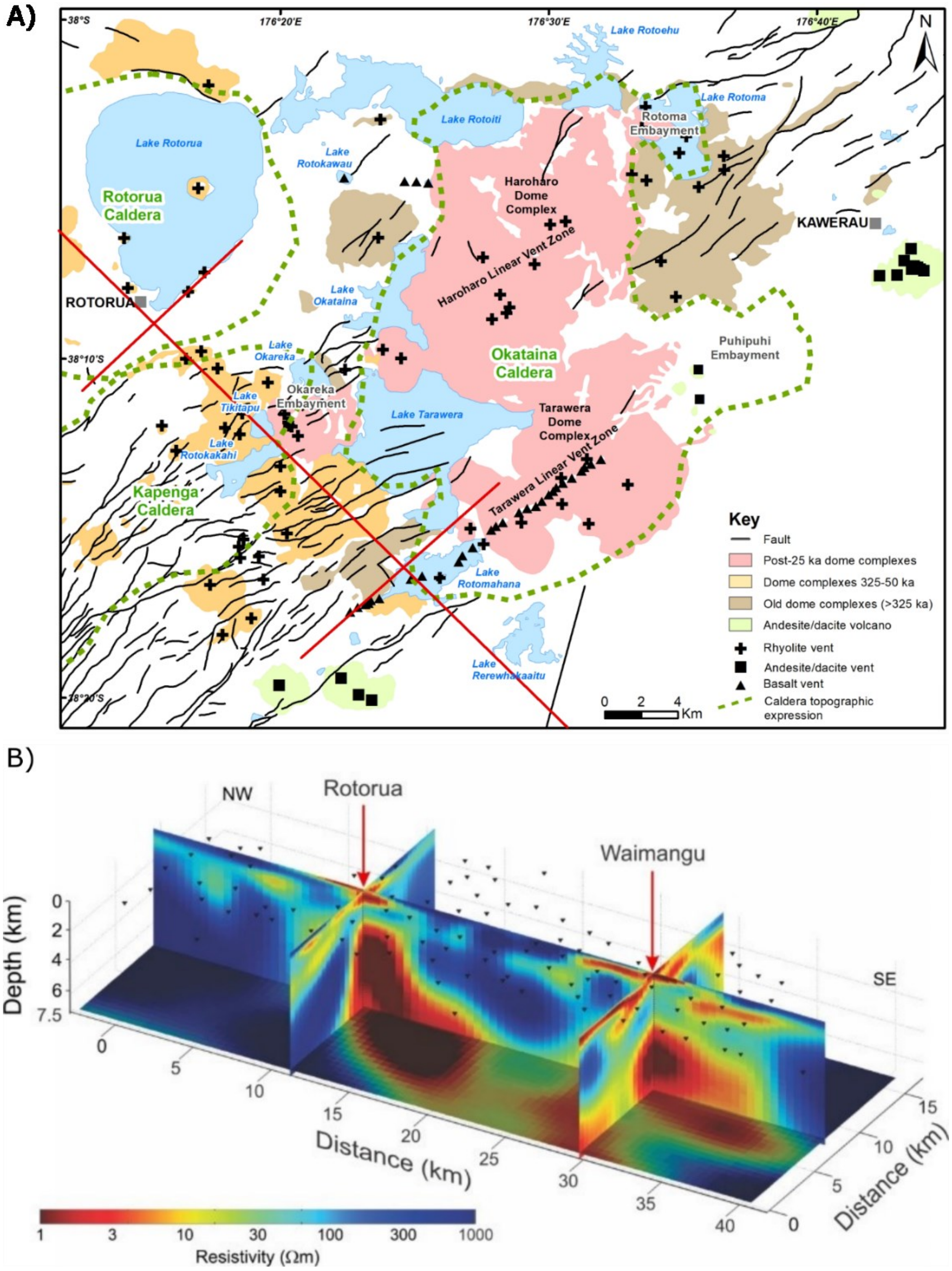

Figure 3: Geological setting of the Okataina Volcanic Centre. a) Simplified volcanic geology of the Okataina Volcanic Centre including lava dome complexes (all of which were deposited in association with multiple pyroclastic eruptives: Nairn, 2002) and their general ages, and locations of the main faults. Red lines are locations of cross-sections presented in b). b) NW–SE and SW–NE cross-sections through the 3-D resistivity model (Heise et al., 2016). Conductors at Rotorua and Waimangu geothermal systems denotes the conductive clay caps. At depth of 2.5 km (Rotorua) and 3.5 km (Waimangu) respectively low resistivity connect the geothermal systems to a wider conductive zone at depth >7 km.

5. NEXT STEPS

Multiple questions can be answered by a scientific drilling programme in the TVZ. At these early days of planning, we are in the process of developing collaborations with scientists and engineers to assist in prioritising the research objectives, planning project goals and well targets, and funding the project. We will work on building relationships with Māori groups so that we can develop a strong programme of not only scientific importance but also recognising the importance of a strong indigenous cultural component. We will consider contemporary issues, such as those relating to the environment and future management of natural resources including Waiariki (geothermal waters). We take an approach founded on traditional concepts of Māori knowledge, new technology applications, environmental planning and monitoring where indigenous approaches, relationship engagement and perspectives are fundamental. Technology developments will also likely be needed in drilling, sampling (fluid and host rock), downhole tools and long-term monitoring techniques in potentially hot areas. We also seek to strengthen links with other ongoing scientific drilling programmes in geothermal and volcanic areas.

6. CONCLUSION

Previous scientific drilling programmes in volcanic and geothermal regions have yielded (and still yield) great scientific and technological advances. The Taupō Volcanic Zone is an exciting natural laboratory at the confluence between subduction, rifting, large silicic volcanism and intense geothermal activity, embedded in an area culturally important and with societal interests ranging from tourism to natural hazards. We are proposing the establishment of a scientific drilling programme in the TVZ to explore four interlinked themes: feedback between arc and rift; timing and rate of geological activity; large-scale hydrology and magma systems; and deep biosphere. We presented the Okataina Volcanic Centre, locus of large silicic eruption, rift segmentation, and high heat flow, as a region with good potential to answer several of the research questions, although the choice of target area and depth will be driven by research questions and community interests. At these early days of planning, we seek to develop a team including Māori groups, and New Zealand and international researchers and engineers, to prioritise the research questions which will be addressed.

ACKNOWLEDGEMENTS

This paper benefited from ongoing discussion with numerous researchers, including Dr. Matthew Stott. It also reflects generous funding over many years from various New Zealand Government science research funding agencies. We also thank our colleagues in the New Zealand research community and geothermal industry partners for their contributions to the studies on which this paper draws.

REFERENCES

Allan, A.S., Wilson, C.J., Millet, M.A., and Wysoczanski, R.J.: The invisible hand: Tectonic triggering and modulation of a rhyolitic supereruption. *Geology*, 40 (2012), 563-566.

Allan, A.S., Morgan, D.J., Wilson, C.J., and Millet, M.A.: From mush to eruption in centuries: assembly of the super-sized Oruanui magma body. *Contributions to Mineralogy and Petrology*, 166, (2013), 143-164.

Anantharaman, K., Brown, C.T., Hug, L.A., Sharon, I., Castelle, C.J., Probst, A.J., Thomas, B.C., Singh, A., Wilkins, M.J., Karaoz, U., and Brodie, E.L.: Thousands of microbial genomes shed light on interconnected biogeochemical processes in an aquifer system. *Nature communications*, 7, (2016), 13219.

Anderson, H. and Webb, T.: The rupture process of the 1987 Edgecumbe earthquake, New Zealand. *New Zealand Journal of Geology and Geophysics*, 32, (1989), 43-52.

Ásmundsson, R., Pezard, P., Sanjuan, B., Henninges, J., Deltombe, J.L., Halladay, N., Lebert, F., Gadalia, A., Millot, R., Gibert, B., and Violay, M.: High temperature instruments and methods developed for supercritical geothermal reservoir characterisation and exploitation-The HiTI project. *Geothermics*, 49, (2014), 90–98.

Barker, S.J., Wilson, C.J., Morgan, D.J., and Rowland, J.V.: Rapid priming, accumulation, and recharge of magma driving recent eruptions at a hyperactive caldera volcano. *Geology*, 44, (2016), 323-326.

Barker, S.J., Van Eaton, A.R., Mastin, L.G., Wilson, C.J.N., Thompson, M.A., Wilson, T.M., Davis, C., and Renwick, J.A.: Modeling ash dispersal from future eruptions of Taupo supervolcano. *Geochemistry, Geophysics, Geosystems*, 20, (2019), 3375–3401.

Bertani, R.: Geothermal power generation in the world 2010-2014 update report. *Geothermics*, 60, (2016), 31–43.

Bertrand, E.A., Caldwell, T.G., Hill, G.J., Wallin, E.L., Bennie, S.L., Cozens, N., Onacha, S.A., Ryan, G.A., Walter, C., Zaino, A., and Wameyo, P.: Magnetotelluric imaging of upper-crustal convection plumes beneath the Taupo Volcanic Zone, New Zealand. *Geophysical Research Letters*, 39, (2012).

Bertrand, E.A., Caldwell, T.G., Hill, G.J., Bennie, S.L., and Soengkono S.: MT imaging of the Ohaaki geothermal system, New Zealand: Implications for locating basement permeability. *Journal of Volcanology and Geothermal Research*, 268, (2013), 36-45.

Bertrand, E.A., Caldwell, T.G., Bannister, S., Soengkono, S., Bennie, S.L., Hill, G.J., and Heise, W.: Using array MT data to image the crustal resistivity structure of the southeastern Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research*, 305, (2015), 63-75.

Bibby, H.M., Caldwell, T.G., Davey, F.J., and Webb, T.H.: Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation. *Journal of Volcanology and Geothermal Research*, 68, (1995), 29–58.

Browne, P. R. L., Graham, I. J., Parker, R. J., and Wood, C. P.: Subsurface andesite lavas and plutonic rocks in the Rotokawa and Ngatamariki geothermal systems, Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research*, 51, (1992), 199–215.

Cant, J.L., Siratovich, P., Cole, J. W., Villeneuve, M.C., and Kennedy, B.M.: Matrix permeability of reservoir rocks, Ngatamariki geothermal field, Taupo Volcanic Zone, New Zealand. *Geothermal Energy*, (2018), 6(2).

Caratori Tontini, F., de Ronde, C., Scott, B., Soengkono, S., Stagpoole, V., Timm, C., and Tivey, M.: Interpretation of Gravity and Magnetic Anomalies at Lake Rotomahana: Geological and Hydrothermal Implication. *Journal of Volcanology and Geothermal Research*, 314, (2016), 84-94.

Carlino, S., Kilburn, C. R. J., Tramelli, A., Troise, C., Somma, R., and De Natale, G.: Tectonic stress and renewed uplift at Campi Flegrei caldera, southern Italy: New insights from caldera drilling. *Earth and Planetary Science Letters*, 420, (2015), 23–29.

Chambefort, I., Lewis, B., Wilson, C.J.N., Rae, A.J., Coutts, C., Bignall, G., and Ireland, T.R.: Stratigraphy and structure of the Ngatamariki geothermal system from new zircon U-Pb geochronology: implications for Taupo Volcanic Zone evolution. *Journal of Volcanology and Geothermal Research,* 274, (2014), 51-70.

Christiansen, R.L.L.: The Quaternary and Pliocene Yellowstone Plateau Volcanic Field of Wyoming, Idaho, and Montana. United States Geological Survey Professional Paper 729-G., (2001), 1–143.

Cole, J.W. and Lewis, K.B.: Evolution of the Taupo-Hikurangi subduction system. *Tectonophysics,* 72, (1981), 1–21

Cole, J.W., Spinks, K.D., Deering, C.D., Nairn, I.A., and Leonard, G.S.: Volcanic and structural evolution of the Okataina Volcanic Centre; dominantly silicic volcanism associated with the Taupo Rift, New Zealand. *Journal of Volcanology and Geothermal Research*, 190, (2010), 123-135.

Cole, J.W., Deering, C.D., Burt, R.M., Sewell, S., Shane, P.A.R., and Matthews, N.E.: Okataina Volcanic Centre, Taupo Volcanic Zone, New Zealand: A review of volcanism and synchronous pluton development in an active, dominantly silicic caldera system. *Earth-Science Reviews*, 128, (2014), 1–17.

Colman, D.R., Poudel, S., Stamps, B.W., Boyd, E.S., and Spear, J.R.: The deep, hot biosphere: Twenty-five years of retrospection. *Proceedings of the National Academy of Sciences*, 114, (2017), 6895-6903.

Corti, G.: Continental rift evolution: From rift initiation to incipient break-up in the Main Ethiopian Rift, East Africa. *Earth-Science Reviews*, 96, (2009), 1–53.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S.: Effects of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. *Geophysical Research Letters*, 21, (1994), 2191–2194.

Dempsey, D.E., Archer, R.A., Ellis, S.M., and Rowland, J.V.: Hydrological effects of dip-slip fault rupture on a hydrothermal plume. *Journal of Geophysical Research: Solid Earth*, 118, (2013), 195-211.

De Ronde, C.E., Fornari, D.J., Ferrini, V.L., Walker, S.L., Davy, B.W., LeBlanc, C., Tontini, F.C., Kukulya, A.L., and Littlefield, R.H.: The Pink and White Terraces of Lake Rotomahana: what was their fate after the 1886 Tarawera Rift eruption? *Journal of Volcanology and Geothermal Research*, 314, (2016), 126-41.

De Ronde, C. E. J., Humphris, S. E., Höfig, T. W., Reyes, A. G., and Scientists, E.: Critical role of caldera collapse in the formation of seafloor mineralization: The case of Brothers volcano. *Geology*, 47, (2019), 1–5.

Downs, D.T., Wilson, C.J.N., Cole, J.W., Rowland, J.V., Calvert, A.T., Leonard, G.S., and Keall, J.M.: Age and eruptive center of the Paeroa Subgroup ignimbrites (Whakamaru Group) within the Taupo Volcanic Zone of New Zealand. *Geological Society of America Bulletin*, 126, (2014), 1131–1144.

Eastwood, A.A., Gravley, D.M., Wilson, C.J.N., Chambefort, I., Oze, C., Cole, J.W., and Ireland, T.R.: U-Pb dating of subsurface pyroclastic deposits (Tahorakuri Formation) at Ngatamariki and Rotokawa geothermal fields. Proceedings, 35th New Zealand Geothermal Workshop, Rotorua, New Zealand, (2013).

Elders, W.A., Fridleifsson, G.Ó., and Albertsson, A.: Drilling into magma and the implications of the Iceland Deep Drilling Project (IDDP) for high-temperature geothermal systems worldwide. *Geothermics*, 49, (2014), 111–118.

Ellis, S.M., Wilson, C.J.N., Bannister, S., Bibby, H.M., Heise, W., Wallace, L., and Patterson, N.: A future magma inflation event under the rhyolitic Taupo volcano, New Zealand: Numerical models based on constraints from geochemical, geological, and geophysical data. *Journal of Volcanology and Geothermal Research*, 168, (2007), 1-27.

Ellis, S. E., Heise, W., Kissling, W., Villamor, P., and Schreurs, G.: The effect of crustal melt on rift dynamics: case study of the Taupo Volcanic Zone. *New Zealand Journal of Geology and Geophysics*, 8306, (2014), 1–6.

Ferrari, L., Orozco-Esquivel, T., Manea, V., and Manea, M.: The dynamic history of the Trans-Mexican Volcanic Belt and the Mexico subduction zone. *Tectonophysics*, 522, (2012), 122-149.

Friðleifsson, G.Ó., Elders, W.A., Zierenberg, R.A., Fowler, A.P., Weisenberger, T.B., Mesfin, K.G., Sigurðsson, Ó., Níelsson, S., Einarsson, G., Óskarsson, F. and Guðnason, E.Á.: The Iceland Deep Drilling Project at Reykjanes: Drilling into the root zone of a black smoker analog. *Journal of Volcanology and Geothermal Research*, (in press).

GNS Science Active Fault Database http://www.gns.cri.nz/Home/Products/Databases/Active-Faults-Database-of-New-Zealand)

Gold, T.: The deep, hot biosphere. *Proceedings of the National Academy of Sciences*, 89, (1992), 6045-6049.

Grant, M.A. and Bixley, P.F.: Geothermal reservoir engineering second edition. Academic Press, (2011).

Grindley, G.W.: The geology, structure and exploitation of the Wairakei Geothermal Field, Taupo, New Zealand. *Bulletin No. 75 New Zealand Geological Survey, Wellington, New Zealand*, (1965), 131 pp

Gualda, G.A., Ghiorso, M.S., Lemons, R.V. and Carley, T.L.: Rhyolite-MELTS: a modified calibration of MELTS optimized for silica-rich, fluid-bearing magmatic systems. *Journal of Petrology*, 53, (2012), 875-890.

Hamilton, A.R., Campbell, K.A., Rowland, J.V., Barker, S., and Guido, D.: Characteristics and variations of sinters in the Coromandel Volcanic Zone: application to epithermal exploration. *New Zealand Journal of Geology and Geophysics*, (2018), 1-19.

Heise, W., Caldwell, T.G., Bibby, H.M., and Bennie, S.L.: Three-dimensional electrical resistivity image of magma beneath an active continental rift, Taupo Volcanic Zone, New Zealand. *Geophysical Research Letters*, (2010), 37.

Heise, W., Caldwell, T. G., Bertrand, E. A., Hill, G. J., Bennie, S. L., and Palmer, N. G.: Imaging the deep source of the Rotorua and Waimangu geothermal fields, Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research*, 314, (2016), 39–48.

Hurst, T., Heise, W., Hreinsdottir, S., and Hamling, I.: Geophysics of the Taupo Volcanic Zone: A review of recent developments. *Geothermics*, 59, (2016), 188–204.

Hurwitz, S. and Lowenstern, J.B.: Dynamics of the Yellowstone hydrothermal system. *Reviews of Geophysics*, 51, (2014), 375–411.

Kamata, H. and Kodama, K.: Volcanic history and tectonics of the Southwest Japan Arc. *Island Arc*, 8, (1999), 393-403.

Jolie, E., Bruhn, D., Hernández, A.L., Liotta, D., Garduño-Monroy, V.H., Lelli, M., Hersir, G.P., Arango-Galván, C., Bonté, D., Calcagno, P., and Deb, P.: GEMex – A Mexican-European Research Cooperation on Development of Superhot and Engineered Geothermal Systems. Proceedings Geothermal Reservoir Engineering Stanford University, (2018), 1–10.

Jørgensen, B.B. and D'Hondt, S.: A starving majority deep beneath the seafloor. *Science*, 314, (2006), 932-934.

Kattenhorn, S.A. and Prockter, L.M.: Evidence for subduction in the ice shell of Europa. *Nature Geoscience*, 7, (2014), 762.

Kennedy, B.M., Holohan, E.P., Stix, J., Gravley, D.M., Davidson, J., and Cole, J.W. Magma plumbing beneath collapse caldera volcanic systems. *Earth-Science Reviews*, 177, (2018), 404–424.

Kissling, W.M. and Weir, G.J.: The spatial distribution of the geothermal fields in the Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research,* 145, (2005), 136-150.

Kissling, W., Ellis, S. E., McNamara, D. D., and Massiot, C.: Modelling Fluid Flow Through Fractured Rock: Examples Using TVZ Geothermal Reservoirs. Proceedings 37th New Zealand Geothermal Workshop, (2015).

Kissling, W.M., Villamor, P., Ellis, S.M., and Rae, A.: Modelling of hydrothermal fluid flow and structural architecture in an extensional basin, Ngakuru Graben, Taupo Rift, New Zealand. *Journal of Volcanology and Geothermal Research*, 357, (2018), 134–151.

Kissling, W., and Massiot, C.: Permeability Anisotropy and Fluid Dispersion in Pervasively Fractured Lavas, Rotokawa Geothermal Field, New Zealand. Proceedings of the World Geothermal Congress (2020).

Lamb, S.: Cenozoic tectonic evolution of the New Zealand plate-boundary zone: a paleomagnetic perspective. *Tectonophysics*, 509, (2011), 135–164.

Langridge, R.M., Ries, W.F., Litchfield, N.J., Villamor, P., Van Dissen, R.J., Barrell, D., Rattenbury, M.S., Heron, D.W., Haubrock, S., Townsend, D.B., Lee, J.M., Berryman, K.R., Nicol, A., Cox, S.C, and Stirling, M.W.: The New Zealand Active Faults Database, New Zealand Journal of Geology and Geophysics, 59, (2016), 86-96.

Leonard, G.S., Begg, J.G., and Wilson, C.J.N. (compilers): Geology of the Rotorua area: scale 1:250,000. Institute of Geological & Nuclear Sciences 1:250,000 geological map 5. Institute of Geological & Nuclear Sciences Limited, Lower Hutt, New Zealand, (2010).

Litchfield, N. J., Van Dissen, R., Sutherland, R., Barnes, P. M., Cox, S. C., Norris, R., … Stirling, M.: A model of active faulting in New Zealand. *New Zealand Journal of Geology and Geophysics*, 57, (2014), 32–56.

Loame, R.C., Villamor, P., Lowe, D.J., Milicich, S.D., Pittari, A., Barker, S.L., Rae, A., Gómez-Vasconcelos, M.G., Martinez-Martos, M., and Ries, W.F.: Using paleoseismology and tephrochronology to reconstruct fault rupturing and hydrothermal activity since c. 40 ka in Taupo Rift, New Zealand. *Quaternary International,* (2019).

Long, P.E., Williams, K.H., Hubbard, S.S., and Banfield, J.F.: Microbial metagenomics reveals climate-relevant subsurface biogeochemical processes. *Trends in microbiology*, 24, (2016), 600-610.

Massiot, C., Nicol, A., McNamara, D. D., and Townend, J.: Evidence for tectonic, lithologic, and thermal controls on fracture system geometries in an andesitic high-temperature geothermal field. *Journal of Geophysical Research: Solid Earth*, (2017), 122.

McMahon S and Parnell J.: Weighing the deep continental biosphere. *FEMS Microbiology Ecology,* 87, (2014), 113-20.

McNamara, D.D., Milicich, S.D., Massiot, C., Villamor, P., McLean, K., Sepulveda, D., and Ries, W.F.: Tectonic controls on Taupo Volcanic Zone geothermal expression: insights from Te Mihi, Wairakei Geothermal Field. *Tectonics*, (2019).

Milicich, S.D., Wilson, C.J.N., Bignall, G., Pezaro, B., Charlier, B.L.A., Wooden, J.L., and Ireland, T.R.: U-Pb dating of zircon in hydrothermally altered rocks of the Kawerau Geothermal Field, Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research,* 253, (2013a), 97–113.

Milicich, S.D., Wilson, C.J.N., Bignall, G., Pezaro, B., and Bardsley, C.: Reconstructing the geological and structural history of an active geothermal field: a case study from New Zealand. *Journal of Volcanology and Geothermal Research,* 262, (2013b), 7–24.

Milicich, S.D., Massiot, C., McNamara, D.D., and Sepulveda, F.: Volcanic Texture Identification and Influence on Permeability Using Borehole Resistivity Image Logs in the Taupo Volcanic Zone, New Zealand. Proceedings, World Geothermal Congress (2020).

Miller, C.A. and Jolly, A.D.: A model for developing best practice volcano monitoring: a combined threat assessment, consultation and network effectiveness approach. *Natural Hazards*, 71, (2014), 493-522.

Ministry of Business, Innovation and Employment, New Zealand Government. Energy in New Zealand, 2017 calendar edition. (2018). ISSN: 2324-5913. www.mbie.govt.nz/info-services/sectors-industries/energy/energydata-modelling/publications/

Moos, D. and Zoback, M.D.: State of stress in the Long Valley caldera, California. *Geology*, 21, (1993), 837–840.

Mortimer, N.: New Zealand's geological foundations. *Gondwana Research*. 7, (2004), 261–272.

Nairn, I.A. and Cole, J.W.: Basalt dikes in the 1886 Tarawera Rift. New Zealand *Journal of Geology and Geophysics*, 24, (1981), 585-592.

Nairn, I.A.: Geology of the Okataina Volcanic Centre, Scale 1:50,000. Institute of Geological and Nuclear Sciences Geological Map 25 25. Lower Hutt: GNS Science, New Zealand, pp. 156. (2002).

Nairn, I. A., Hedenquist, J. W., Villamor, P., Berryman, K. R., and Shane, P. A.: The ∼AD1315 Tarawera and Waiotapu eruptions, New Zealand: Contemporaneous rhyolite and hydrothermal eruptions driven by an arrested basalt dike system? *Bulletin of Volcanology*, 67, (2005), 186–193.

Nakada, S., Uto, K., Sakuma, S., Eichelberger, J., and Shimizu, H.: Scientific Results of Conduit Drilling in the Unzen Scientific Drilling Project (USDP). *Scientific Drilling*, 1, (2005), 18-22.

Onstott, T.C.: Deep life: the hunt for the hidden biology of earth, Mars, and beyond. Princeton University Press. (2016).

Pálsson, B., Hólmgeirsson, S., Guomundsson, Á., Bóasson, H. Á., Ingason, K., Sverrisson, H., and Thórhallsson, S.: Drilling of the well IDDP-1. *Geothermics*, 49, (2014), 23–30.

Parkes, R.J., Cragg, B., Roussel, E., Webster, G., Weightman, A., and Sass, H.: A review of prokaryotic populations and processes in sub-seafloor sediments, including biosphere: geosphere interactions. *Marine Geology*, 352, (2014), 409-425.

Parson, L.M. and Wright, I.C.: The Lau-Havre-Taupo back-arc basin: A southward-propagating, multi-stage evolution from rifting to spreading. *Tectonophysics*, 263(1-4), (1996), 1-22.

Plag, H.P., Brocklebank, S., Brosnan, D., Campus, P., Cloetingh, S., Jules-Plag, S., and Stein, S. Extreme geohazards: reducing the disaster risk and increasing resilience: a community science position paper. European Science Foundation, Group on Earth Observations, Geohazard Community of Practice, 67pp. (2015).

Power, J. F., Carere, C. R., Lee, C. K., Wakerley, G. L. J., Evans, D. W., Button, M., White, D., Climo, M.D., Hinze, A.M., Morgan, X.C., McDonald, I.R., Cary, S.C., and Stott, M. B.: Microbial biogeography of 925 geothermal springs in New Zealand. *Nature Communications*, (2018), 9(1).

Reinsch, T., Dobson, P., Asanuma, H., Huenges, E., Poletto, F., and Sanjuan, B.: Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities. *Geothermal Energy*, 5, (2017), 16.

Rosenberg, M.D.: Volcanic and tectonic perspectives on the age and evolution of the Wairakei-Tauhara geothermal system. Ph.D. thesis, Victoria University, Wellington, New Zealand. (2017)

Rowland, J.V. and Simmons, S.F.: Hydrologic, magmatic, and tectonic controls on hydrothermal flow, Taupo Volcanic Zone, New Zealand: Implications for the formation of epithermal vein deposits. *Economic Geology*, 107, (2012), 427-457.

Rowland, J.V. and Sibson, R.H.: Extensional fault kinematics within the Taupo Volcanic Zone, New Zealand: Soft-linked segmentation of a continental rift system. *New Zealand Journal of Geology and Geophysics*, 44, (2001), 271-283.

Rowland, J. V. and Sibson, R. H.: Structural controls on hydrothermal flow in a segmented rift system, Taupo Volcanic Zone, New Zealand. *Geofluids*, 4, (2004), 259–283.

Rundle, J.B. and Eichelberger, J.C.: Science guide for the Long Valley caldera deep hole (No. SAND-89-0155). Sandia National Labs., Albuquerque, NM (USA). (1989)

Schloss, P.D., Girard, R.A., Martin, T., Edwards, J., and Thrash, J.C.: Status of the archaeal and bacterial census: an update. *MBio*, 7, (2016), e00201-16.

Seebeck, H. C. and Nicol, A.: Dike intrusion and displacement accumulation at the intersection of the Okataina Volcanic Centre and Paeroa Fault zone, Taupo Rift, New Zealand. *Tectonophysics*, 475, (2009), 575–585.

Seebeck, H. C., Nicol, A., Stern, T. a., Bibby, H. M., and Stagpoole, V.: Fault controls on the geometry and location of the Okataina Caldera, Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research*, 190, (2010), 136–151.

Seebeck, H., Nicol, A., Giba, M., Pettinga, J., and Walsh, J.: Geometry of the subducting Pacific plate since 20 Ma, Hikurangi margin, New Zealand. *Journal of the Geological Society*, 171, (2014a), 131–143.

Seebeck, H., Nicol, A., Walsh, J.J., Childs, C., Beetham, R.D., and Pettinga, J.: Fluid flow in fault zones from an active rift. *Journal of Structural Geology*, 62, (2014b), 52-64.

Simmons, S.F., Brown, K.L., Browne, P.R., and Rowland, J.V.: Gold and silver resources in Taupo Volcanic Zone geothermal systems. *Geothermics*, 59, (2016), 205-214.

Siratovich, P., Heap, M. J., Villeneuve, M. C., Cole, J. W., and Reuschle, T.: Physical property relationships of the Rotokawa Andesite, a significant geothermal reservoir rock in the Taupo Volcanic Zone, New Zealand. *Geothermal Energy*, (2014), 2(10).

Sherburn, S., Bannister, S. C., and Hurst, A. W.: Shallow seismicity of the central Taupo Volcanic Zone, New Zealand: its distribution and nature. *New Zealand Journal of Geology and Geophysics*, 42, (2000), 533–542.

Smith, V. C., Shane, P., and Nairn, I. A.: Trends in rhyolite geochemistry, mineralogy, and magma storage during the last 50 kyr at Okataina and Taupo volcanic centres, Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research*, 148, (2005), 372–406.

Smith, I.E.M. and Price, R.C.: Tonga-Kermadec arc and Havre-Lau back-arc system: their role in the development of tectonic and magmatic models for the western Pacific. *Journal of Volcanology and Geothermal Research*, 156, (2006), 315–331.

Stern, T.A.: Asymmetric back-arc spreading, heat flux and structure associated with the Central Volcanic Region of New Zealand. *Earth and Planetary Science Letters*, 85, (1987), 265-276.

Timm, C., Davy, B., Haase, K., Hoernle, K.A., Graham, I.J., De Ronde, C.E., Woodhead, J., Bassett, D., Hauff, F., Mortimer, N., and Seebeck, H.C.: Subduction of the oceanic Hikurangi Plateau and its impact on the Kermadec arc. *Nature Communications*, 5, (2014), 4923.

Tivey, M.A., de Ronde, C.E.J., Caratori Tontini, F., Walker, S., and Fornari, D.J.: A novel heat flux study of a geothermally active lake – Lake Rotomahana, New Zealand. *Journal of Volcanology and Geothermal Resources*, 314, (2016), 95-109.

Villamor, P., Berryman, K.R., Nairn, I.A., Wilson, K., Litchfield, N., and Ries, W.: Associations between volcanic eruptions from Okataina volcanic center and surface rupture of nearby active faults, Taupo rift, New Zealand: Insights into the nature of volcano-tectonic interactions. *GSA Bulletin*, 123, (2011), 1383-1405.

Villamor, P., Berryman, K. R., Ellis, S. E., Schreurs, G., Wallace, L. M., Leonard, G. S., Langridge, R.M., and Ries, W. F. Rapid evolution of subduction-related continental intra-arc rifts: The Taupo Rift, New Zealand. *Tectonics*, (2017), 1–64.

Villamor, P., Nicol, A., Seebeck, H., Rowland, J., Townsend, D., Massiot, C., McNamara, D.D., Milicich, S.D., Ries, W., and Alcaraz, S.: Tectonic structure and permeability in the Taupō Rift: New insights from analysis of LIDAR derived DEMs. Proceedings 39th New Zealand Geothermal Workshop. (2017b).

Wallace, L.M., Beavan, J., McCaffrey, R., Darby, D.J.: Subduction zone coupling and tectonic block rotations in the North Island, New Zealand. *Journal of Geophysical Research*, 109, (2004), B12406.

Wallis, I.C., McNamara, D., Rowland, J.V., and Massiot, C.: The nature of fracture permeability in the basement greywacke at Kawerau Geothermal Field, New Zealand. 9 p. In: Proceedings, thirty–seventh Workshop on Geothermal Reservoir Engineering, January 30 – February 1, 2012, Stanford University. Stanford, California.: Stanford University. Stanford Geothermal Program Workshop report SGP–TR–194. (2012).

Watanabe, N., Numakura, T., Sakaguchi, K., Saishu, H., Okamoto, A., Ingebritsen, S. E., and Tsuchiya, N.: Potentially exploitable supercritical geothermal resources in the ductile crust. *Nature Geoscience*, (2017), 1–6.

Whitman W.B., Coleman D.C., and Wiebe W.J.: Prokaryotes: The unseen majority. *Proceedings of the National Academy of Sciences*, 95, (1998), 6578-83.

Wilkins, M.J., Daly, R., Mouser, P.J., Trexler, R., Wrighton, K.C., Sharma, S., Cole, D.R., Biddle, J.F., Denis, E., Fredrickson, J.K., and Kieft, T.L.: Trends and future challenges in sampling the deep terrestrial biosphere. *Frontiers in Microbiology*, 5, (2014), 481.

White, B. R., and Chambefort, I.: Geothermal development history of the Taupo Volcanic Zone. *Geothermics*, 59, (2016), 148–167.

Wilson, C.J.N., Rogan, A.M., Smith, I.E.M., Northey, D.J., Nairn, I.A., and Houghton, B.F.: Caldera Volcanoes of the Taupo Volcanic Zone, New Zealand, *Journal of Geophysical Research. Solid Earth and Planets*, 89, (1984), 8463-8484.

Wilson, C. J. N., Houghton, B. F., McWilliams, M. O., Lanphere, M. A., Weaver, S. D., and Briggs, R. M.: Volcanic and structural evolution of Taupo Volcanic Zone, New-Zealand: a review. *Journal of Volcanology and Geothermal Research*, 68, (1995), 1–28.

Wilson, C.J.N., Charlier, B.L.A., Fagan, C.J., Spinks, K.D., Gravley, D.M., Simmons, S.F., and Browne, P.R.L.: U–Pb dating of zircon in hydrothermally altered rocks as a correlation tool: application to the Mangakino geothermal field, New Zealand. *Journal of Volcanology and Geothermal Research,* 176, (2008), 191–198.

Wilson, C.J.N., Gravley, D.M., Leonard, G.S., and Rowland, J.V.: Volcanism in the central Taupo Volcanic Zone, New Zealand: tempo, styles and controls. In: Studies in Volcanology: the Legacy of George Walker. Special Publications of IAVCEI, 2, (2009), 225-247.

Wilson, C.J.N., Charlier, B.L.A., Rowland, J.V., and Browne, P.R.L.: U–Pb dating of zircon in subsurface, hydrothermally altered pyroclastic deposits and implications for subsidence in a magmatically active rift: Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research,* 191, (2010), 69–78.

Wilson, C.J.N. and Rowland, J.V.: The volcanic, magmatic and tectonic setting of the Taupo Volcanic Zone, New Zealand, reviewed from a geothermal perspective. *Geothermics*, 59, (2016), 168–187.

Wyering, L. D., Villeneuve, M. C., Kennedy, B. M., Gravley, D. M., and Siratovich, P.: Using drilling and geological parameters to estimate rock strength in hydrothermally altered rock? A comparison of mechanical specific energy, R/N-W/D chart and Alteration Strength Index. *Geothermics*, 69, (2017), 119–131.

Zarrouk, S.J. and McLean, K.: Geothermal Well Test Analysis: Fundamentals, Applications and Advanced Techniques. Academic Press. (2019).

Zemanek, J., Glen, E.E., Jr., Norton, L.J., and Caldwell, R.L.: Formation evaluation by inspection with the borehole televiewer. *Geophysics*, 35, (1970), 254-269.

Ziegler, M., Rajabi, M., Heidbach, O., Hersir, G. P., Ágústsson, K., Árnadóttir, S., and Zang, A.: The stress pattern of Iceland. *Tectonophysics*, 674, (2016), 101–113.