THE MAGMATIC-HYDROTHERMAL TRANSITION OF THE TAUPO VOLCANIC ZONE, NEW ZEALAND

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ABSTRACT

The Taupo Volcanic Zone (TVZ), New Zealand is a rifting arc that produced over the last 2 My over 6000 km^3 of caldera-associated volcanic products. About four times as much magma is estimated to be trapped at depth below the central TVZ than is erupted, feeding heat, volatiles and chemicals into 23 geothermal systems with a total of ca. 4.2 GW thermal energy release. We present here a combined study linking melt, hypersaline and dilute fluid inclusion chemistry, surface and reservoir fluid chemistry and whole rock lithochemistry and discuss the magmatic-hydrothermal chemical zoning in large silicic systems.

New dataset of full lithogeochemistry (Chambefort and Dilles 2015) in active geothermal systems of the TVZ refine the zoned chemical footprint left by both dilute meteoric-dominated and magmatic-hydrothermal fluids. Altered whole rock trace elements content (including precious metals and volatiles) shows major variation with depth, due to the influence of past hydrothermal activity, magmatic degassing, natural variability of the reservoir rocks, and current active fluid-rock interactions. The concentrations of Li, Cs, Tl, Bi, Sn, Ag, Se, Te, as well as Au, generally increase upward toward the paleosurface, where they are 10-100 times greater than near known or potentially 'active' intrusions. New direct in–situ analyses of trapped fluid inclusions in phenocrysts and hydrothermal veins associated with magmatic subsolidus crystallization are compared with liquid-dominated dilute fluid inclusions and geothermal fluids Li, Cs, B, Na, Cl, K content (and precious metals) providing a unique direct assessment of the role of each component (magma, rock, fluids) in New Zealand's world known geothermal systems.

1. INTRODUCTION

How magmas and geothermal systems are connected? Why geothermal systems of New Zealand are located where they are? How do they evolve in time from natural cause? Since the settlement of Te Arawa, New Zealand geothermal systems have triggered interest and fascination. Our society has always felt strongly connected with these exceptional lands, and research to answer these fundamental questions. Since the development of electricity generation, scientists have been refining geothermal geological models. This work proposes to add a little stone to our cultural heritage.

In 1992, Werner F. Giggenbach gave a Distinguished Lecture to the Society of Economic Geologists where he underlined a recurrent point between scientists '…*the commitment of the geological fraternity to the magmatic cause usually consisted of more or less artistically executed magic arrows marked "magmatic fluid" or even less specific "magmatic input" pointing up from some nether regions where anything could happen*.' Other the years, Giggenbach, and esteemed geologists refined the compositions of these '*mag(mat)ic'* arrows using chemical, isotopic, gas and water analyses, and lately with the development of in-situ techniques fluid inclusion compositions in ore deposit environments. These led to the concept of 'andesitic water' and the andesitic – rhyolite source of Taupo Volcanic Zone geothermal systems (Giggenbach, 1992a,b, 1995). Geothermal and volcanic /magmatic activities in the TVZ are certainly closely related (Wilson and Rowland, 2015). Recent volcanic episodes, such as the Mount Tarawera eruption in 1886, induced irreversible hydrological change of the Rotomahana-Waimangu hydrothermal system, with the partial destruction of the pink and white terraces and the creation of the Waimangu geothermal system (Simmons et al., 1993).

For the last 20 years the Henley and Ellis (1983) and Giggenbach (1995) models have been the almost unique references to the geological framework of New Zealand geothermal systems. In the last 5 years, however, research projects such as Hotter and Deeper (GNS Science, now Geothermal resource of New Zealand), Source to Surface (MRP-University of Canterbury), Marsden Fingerprinting geothermal Fluids: Tracking the magmatic signature, and numerous student/universities initiatives have drastically increase our knowledge on the deep crustal conditions of the Taupo Volcanic Zone.

Yet the nature of the deep primary fluids exsolving from magma bodies and the heating mechanism of these geothermal systems still remain equivocal.

New insights into the nature and presence of magma bodies in the crust are needed to provide fundamental information to underpin volcanology and geothermal research. Additionally, targeting of deeper wells (at depths of >4 km), inevitable for future geothermal development (Bignall and Carey, 2011; Hashiba et al., 2001), will require knowing (i) the chemical composition (i.e. the unique fingerprint) of the primary exsolved fluids (intermediate versus felsic composition), and (ii) the spatial distribution of deep-seated magma bodies.

It remains to determine: 1) how deep magmatic processes and shallow geothermal systems are linked? 2) what is the composition of the 'andesitic water' and 3) what is the magmatic-hydrothermal chemical transition in the Taupo Volcanic Zone?

2. TAUPO VOLCANIC ZONE GEOTHERMAL SYSTEMS

The Taupo Volcanic Zone (TVZ), New Zealand is a rifting arc that produced over the last 2 My over 6000 km^3 of caldera-associated volcanics. About four times as much magma is estimated to be trapped at depth below the central TVZ than is erupted, feeding heat, volatiles and chemicals into 23 geothermal systems with a total of ca. 4.2 GW thermal energy release.

The TVZ geothermal systems are fed by heat at depth, inducing a large convective cell of mainly meteoric waters with a small proportional input of magmatic-derived fluids (the *mag(mat)ic* arrow!). A recent geophysical investigation has suggested that observed low resistivity plumes underneath some TVZ geothermal fields are likely to be associated with fluid rising via large basement structures (Bertrand et al., 2012), and / or shallow intrusion Bertrand et al., 2015). The gas content in shallow (1-3 km depth) TVZ well discharges, and in surface chemistry measurements indicate exsolved magmatic hydrogen and oxygen are present in small quantities (~ 10% of the andesitic water) (Giggenbach, 1995). Giggenbach proposed that geothermal systems in the western TVZ (e.g. Wairakei-Tauhara, Mokai) are influenced by "mantle-type" volatiles introduced via underlying rhyolitic magmatism based on low CO_2/Cl ratios. Conversely, eastern TVZ geothermal fields (e.g. Rotokawa, Ohaaki-Broadlands, Kawerau) were influenced by "andesitic" arc-type volatiles characterised by high CO_2/Cl ratios.

2.1 Ngatamariki geothermal system: a proxy to active degassing intrusion environment

An intrusive magmatic complex has been intercepted in the Ngatamariki Geothermal Fields. The complex represents a relict proxy of the thermo-chemical conditions occurring in the TVZ crust above a shallow intrusion (Fig. 2).

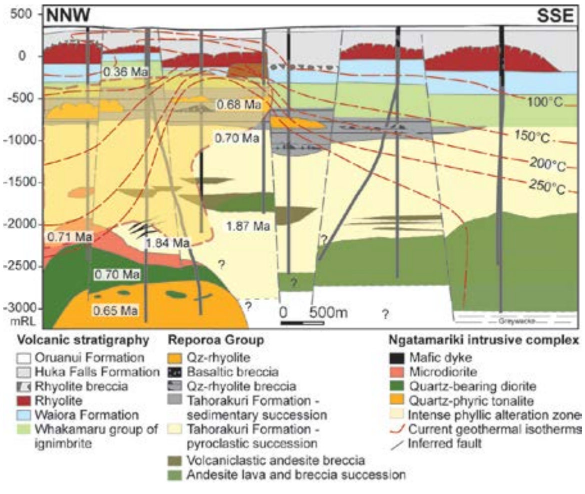

Figure 2: NNW-SSE geological cross-section of the Ngatamariki Field (Chambefort et al., 2014).

A diorite, microdiorite, tonalite and rare mafic dykes emplaced between 0.71 and 0.65 Ma. They formed at depth an intrusion of ~ 5 km^3 minimum. Rare surface lavas emplaced at the same time approximately 2000 m above the intrusions (Chambefort et al., 2014).

The intrusions emplaced in the pyroclastic succession of the Tahorakuri Formation. A large hydrothermal alteration halo formed simultaneously with the magmatism. The high temperature deep acidic fluids created a hydrothermal alteration mineral zoning similar to those observed in porphyry copper environment (Chambefort et al., 2015).

Evidences for subsolidus undercooling fast crystallisation texture in the tonalite, 'wispy' quartz veins in the diorite and quartz vein stockworks in the wall rock attest of the release and circulation of 'mag(mat)ic' exsolved fluids (Fig. 3).

3. METHODS

Whole rock major and trace element geochemical analyses were realised by ALS Chemex in Vancouver Canada. Major elements and gold were analysed by ICP-MS, carbon and sulfur by combustion furnace, resistive elements by lithium borate fusion, base metals by four acid digestion, and gold-related trace elements by aqua regia digestion. Cathodoluminescence imaging was conducted (at the University of Canterbury, New Zealand) to characterise the crystallisation and post-crystallisation history of the magmatic quartz phenocrysts, and link these to the trapping history of the fluid inclusions (e.g. primary fluid inclusions: entrapment during the quartz crystallisation associated with magmatic degassing, versus secondary fluid inclusions: entrapment during a subsequent, post-degassing hydrothermal event). Microthermometry measurements (at GNS Science, New Zealand) was undertaken to obtain the range of salinity and homogenisation temperatures of the different fluids.

Direct *in situ* mass-spectrometry analyses of volatiles and trace elements in vapour and brine fluid inclusions are challenging (as the trapped fluids are dilute) and have not previously been undertaken for New Zealand active geothermal systems. This approach is possible with *in situ* analytical techniques such as laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) (Heinrich et al., 1999, 2003). Ngatamariki fluid inclusions were analysed for trace elements and volatile contents at ETH-Zurich (Switzerland) in collaboration with AI Prof Heinrich, and compare with dilute fluid inclusion analyses from Rotokawa and Ohaaki Geothermal Fields, as well as published melt inclusion compositions. Using a prototype excimer ArF laser (193 nm) the sample material was ablated (craters of 5 - 100 microns in diameter) and then flushed into an Elan6100 DRC quadrupole ICP mass spectrometer for "simultaneous" multi-element analysis. Recent developments in this technique allow for quantitative analysis of volatiles, along with trace elements, in small (~20 micron) fluid inclusions trapped in minerals (Seo et al., 2011). Estimates were obtained of the fractionation of elements (sulphur, chlorine, boron, bromine, lithium, arsenic and antimony and others) between the vapour and brine phase at the inferred magmatic and geothermal reservoir conditions.

4. RESULTS AND IMPLICATIONS

Undercooling and fast crystallisation textures such as myrmekites, granophyric, dendritic and skeletal growths have often been associated with subsolidus crystallisation due to H_2O loss. The exsolution of the fluid phase initiates the nucleation of quartz, K-feldspar and plagioclase by quenching at the binary eutectic.

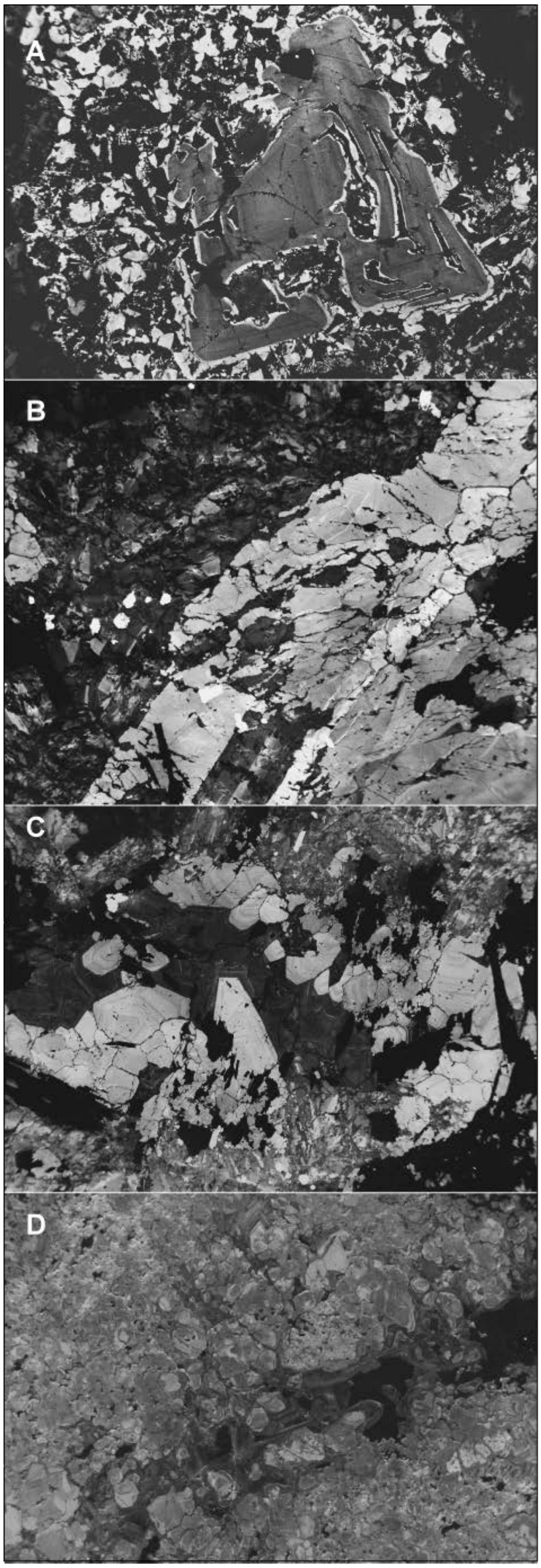

Figure 3: Cathodoluminescence pictures of quartz at Ngatamariki. A: Skeletal quartz indicating subsolidus fast crystallisation in the tonalite, B: Wispy, irregular, quartz vein in the diorite, C: Well crystallised quartz vein in the diorite, D: Intense silicification and quartz vein in the Tahorakuri Tuff above the intrusions.

The intrusions underwent phase separation at an estimated depth of ~2 km. The working hypothesis is that the last stage of the magmatic mineralogy has recorded the exsolution stage in their chemistry. Quartz phenocrysts in the tonalite are up to 8 mm in diameter and embayed. Also present are small (<2 mm) skeletal quartz grains cocrystallising with a myrmekitic / granophyric groudmass.

The outer rims of the skeletal quartz and groundmass quartz are brighter in CL than the large phenocrysts, suggesting enrichment in Ti and other trace elements (Fig. 3).

Hypersaline fluid inclusions trapped in rhyolite skeletal phenocrysts are enriched in B, Cs and Li compared to hydrothermal fluids trapped in inclusions in veins hosted in diorite. Dilute meteoric-dominated chloride fluids are enriched in Li, Cl, as well as K and Ca, but are depleted in B. Preliminary results on Cl and Br content of the fluid inclusions show that fractionation of these elements occurs during phase separation at the magmatic-hydrothermal interface and heterogeneous trapping in this deep environment.

Hypersaline fluids exsolving from a diorite are enriched in Pb, Cu and Zn compared to rhyolite fluid inclusions but the latter appear to be enriched in Ag. Positive correlation between Pb, Zn, Ag, As and Cs, B and Li is interpreted to be linked to vapor loss.

5. CONCLUSIONS

The composition of brine and vapour exsolving from a magmas underneath the Taupo Volcanic Zone have been for the first time analysed. They are presented in this Keynote talk. We have now the possibility to compare these results with surface and calculated reservoir compositions (Giggenbach, 1995) and direct sampling (Simmons and Brown, 2007). We can now assess the role of each component (magma, rock, fluids) in New Zealand's world known geothermal systems.

But why this is important?

The TVZ represents one of the largest active degassing areas on the planet, with a total crustal heat transfer of ~2600 MW/100 km^2, largely through the convective geothermal systems present. Geothermal energy in high temperature systems (>240ºC) accounts for approximately 13% of New Zealand's electricity generation and is forecasted to reach ~20% by 2020 (Bignall and Carey, 2011). To increase productivity, the geothermal industry is focusing on targeting deep-seated permeability (>4 km) to minimise environmental impact and improve efficiencies. This research constrains geothermal well chemistry and contributes to the development of chemical exploration tools for the enhancement of deep (>4 km) geothermal well targeting.

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