DEEP GEOTHERMAL RESOURCES IN THE TVZ: RESEARCH STRATEGIES AND DIRECTIONS AT IGNS

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ABSTRACT

A 6-year multi-disciplinary programme is under way at IGNS which aims to characterise geothermal reservoir environments at depths of 2 - 4 km in the Taupo Volcanic Zone (TVZ), and thereby provide a framework of understanding on which deep exploration and production programmes can be based. Emphasis is placed on determining the P-T-X constraints of the near-heat source regions, and on developing techniques that can be used to explore for them. The nature of the thermal boundaries of the fields is also being studied in order to better understand processes affecting recharge at depth. Ultimately, this work will constrain large scale models of the evolution of TVZ geothermal systems.

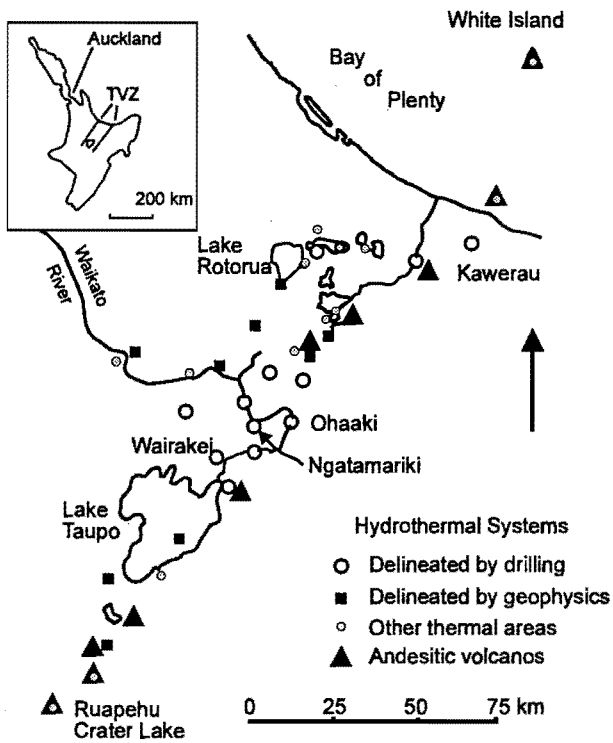
INTRODUCTION

Recent NZ Government strategy papers have acknowledged that NZ will become more dependent on its geothermal resources for power production into the next century, particularly as local reserves of natural gas are depleted. Indeed, given that an estimated 12,000 GWh of energy, or more than one third of the country's current energy requirements, are contained within New Zealand's *known* geothermal resources (Fig. 1), it is sensible that these resources be utilised.

However, experience with production from < 1500 m depth at Wairakei, Kawerau and more recently Ohaaki has shown that sustainability of the resources is an issue, not only with regard to steam supply, but also from an environmental perspective. Subsidence, cold inflows and/or the destruction of natural features at Wairakei and Kawerau, and the rapid rundowns experienced at Ohaaki all demonstrate the problems inherent in the current approach to geothermal development. A more sustainable approach, and one which has been identified in the 1995 NZ Energy Strategy document, would be to draw production fluids from deeper (ie. 2-4 km), higher temperature environments than is presently practiced.

However, little is presently known of the deeper reservoir environments of the TVZ geothermal systems. This, combined with the high costs of deep drilling and the emphasis on high success rates from production drilling, leave commercial geothermal developers/operators unwilling to accept the risks associated with deep exploration. In response to this problem, scientists at IGNS (in conjunction with the NZ Foundation for Research, Science and Technology and a number of other collaborating organisations), have embarked on a 6 year programme of study to delineate the chemical and physical characteristics of the heat source regions of the TVZ geothermal systems. The ultimate goal of this work is to provide a framework of understanding on which future deep exploration and production strategies might be developed.

Fig. 1. Location map of TVZ geothermal systems.



Key questions which this programme aims to address include:

- What are the P-T-X characteristics of the reservoir in the vicinity of the magmatic heat sources? What are the key chemical and physical processes operating there, and what are some likely production scenarios for these environments?
- How does recharge occur in the heat source region? Are shallow and deep thermal boundary zones fundamentally different? Are hot-dry-rock production techniques feasible for such environments?
- What geophysical and geochemical techniques are most effective in exploring these regions?

Current projects aimed at resolving these issues are discussed in the following sections.

THE MAGMA-HYDROTHERMAL CONNECTION IN THE TVZ

Direct evidence of the location of present-day magmatic heat sources in TVZ systems is lacking. Despite the fact that nearly all of the systems are juxtaposed to either Pleistocene or Holocene andesitic volcanoes or to ring fault structures associated with large silicic eruptive centres, all discharges from the presently explored systems are dominated by meteoric water, with only a small fraction (up to 14 %) possibly deriving from andesitic magma (Giggenbach, 1996). Although the ultimate source of the principle volatile species in the TVZ geothermal fluids (eg. C, S, N, Cl) is "magmatic" (Giggenbach, 1996), none of the TVZ heat sources have been located to date.

Similarly, few clues as to heat source location are forthcoming from hydrothermal alteration studies of the active systems, most of which have found alteration assemblages to be largely in equilibrium with present-day alkaline-chloride production fluids (eg. Wairakei, Steiner (1977); Waiotapu, Hedenquist and Browne, 1989; Ohaaki, Browne and Ellis, 1970). Evidence of past magmatic interaction within TVZ hydrothermal reservoirs is found in just two systems, at Kawerau (Christenson, 1989, 1995) and Ngatamariki (Wood, unpublished data).

Studies at Kawerau have revealed that at least two transient magmatic events significantly altered the equilibrium state of that hydrothermal system in the past. Two dacitic extrusives occupying positions along the current western margin of the field have $^{40}Ar/^{39}Ar$ of 138 ± 7 ka (M.O. McWilliams, pers comm 1995), making them considerably younger than the 200 ka minimum age of the hydrothermal system reported by Browne (1979). This, and other geological evidence, suggests that the domes were intruded through an active hydrothermal reservoir. More recently, extrusion of the andesitic massif of Mt Edgecumbe situated at the southeast margin of the field occurred between ca 14.5 and 1 ka and resulted in extensive hydrothermal eruptions from the system (Nairn and Wiradiradja, 1981).

Whereas present day (ie. open fracture) mineralisation is in chemical and isotopic equilibrium with present day reservoir fluids (Christenson, 1987), hydrothermal alteration in stockwork mineralisation adjacent to the Onepu Domes and in sealed hydrofractures associated with the hydrothermal eruptions along the south-east side of the field have distinctive parageneses and stable isotope signatures.

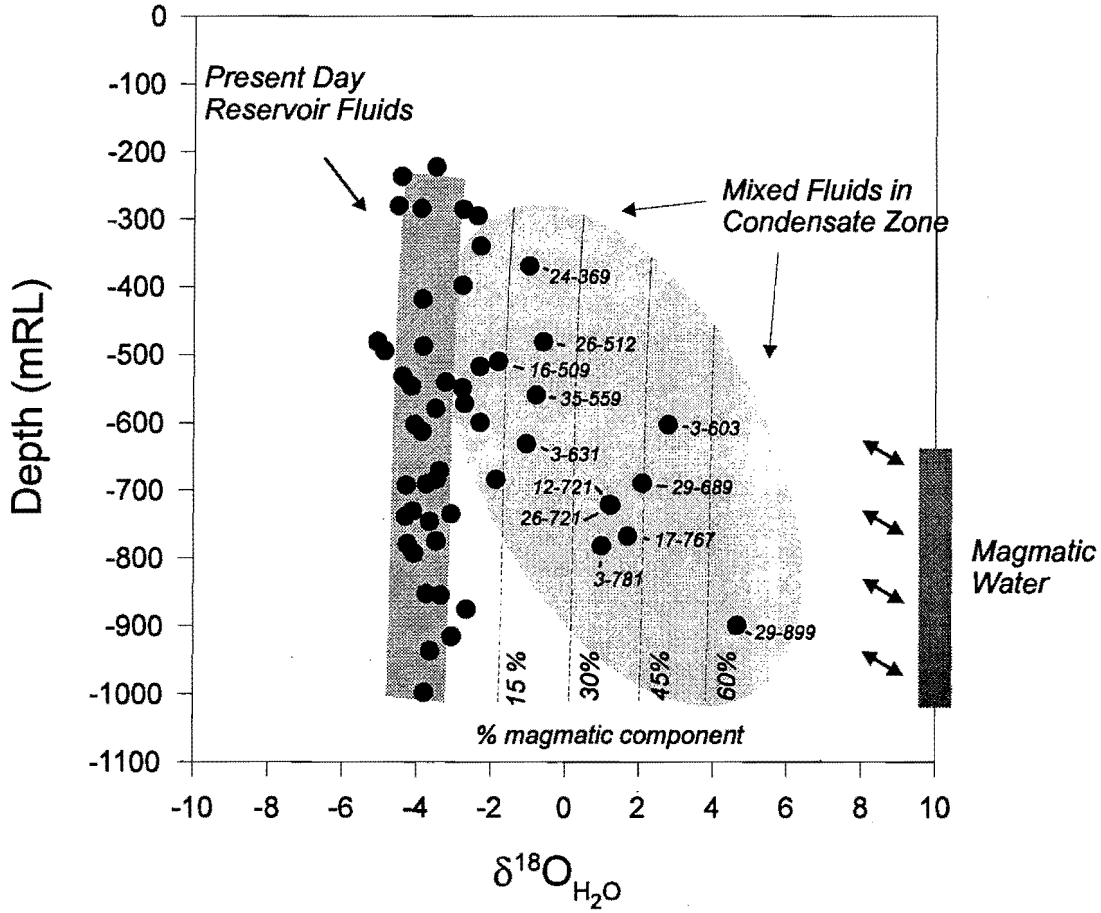
Table 1. Occurrence of mineral assemblages bearing magmatic signatures in the Kawerau systems.

MRL	quartz	adularia	anhydrite	hematite	calcite	wairakite	pyrite
3-571	•		•	•	•		•
3-603	•	•	•		•		•
3-631	•	•	•		•	•	•
3-781	•	•			•		•
10-701	•	•		•	•	•	•
12-721	•	•	•	•	•	•	•
16-509	•				•		•
17-737	•			•	•		
17-767	•	•			•	•	•
35-559	•		•	•	•		•
29-689	•			•	•		
29-899	•				•		•

Quartz, adularia, calcite and wairakite are common alteration phases in NZ geothermal systems, but hematite and anhydrite (Table 1) are exceedingly rare and are indicative of redox conditions rather more oxidising than those observed in present-day reservoirs. Fluid inclusion analyses on quartz and calcite from these distinctive veins show the parent fluids were uniformly at or near boiling point for their respective depths. Using this information, and the $\delta^{18}O$ signatures from calcite and quartz to calculate the $\delta^{18}O$ of the equilibrium parent fluid, we find that the parent fluids were strongly enriched with respect to ^{18}O relative to both "normal" vein assemblages and to

present day waters in the system (Fig. 2). Adopting the assumption that variations from present day meteoric water signatures of more than 1 per mil above the meteoric values are due to mixing of "magmatic water" (eg. Giggenbach, 1996), mixing fractions of up to 60% magmatic water component are obtained for some of the parent fluids.

Fig. 2. $\delta^{18}O$ compositions of paleo-fluids in the Kawerau hydrothermal system.

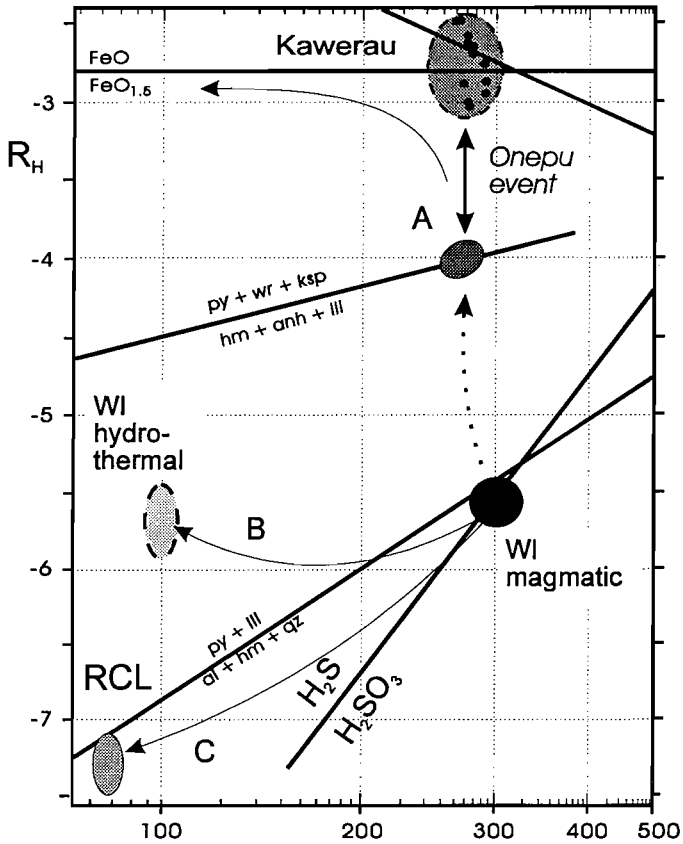


That the oxidation state of fluids which precipitated the isotopically heavy calcite is significantly higher than the present day fluids is evident from Fig. 3. The R_H (=log (fH_2/fH_2O) values of present day production discharges plot uniformly along the $FeO/FeO_{1.5}$ rock buffer described by Giggenbach (1986). For comparison, also plotted on the diagram are the nominal locations for magmatic fluids of similar temperature from White Island, lower temperature "hydrothermal" fluids from White Island, and a field representing acid crater lake environments, such as that observed on Mt. Ruapehu. The equilibrium reaction:

pyrite + wairakite + adularia = hematite + anhydrite + illite

occupies a region which is intermediate between gas buffered magmatic fluids and those resident in the present day geothermal reservoir, and is consistent with mixing between these end-member compositions.

Fig. 3. Oxidation state of past and present Kawerau reservoir fluids.



Fluid mixing is readily simulated using thermodynamic reaction path models. The value of such models is that they provide multi-component views of complicated geochemical interactions, and offer a complete picture of the physical and chemical state of a system.

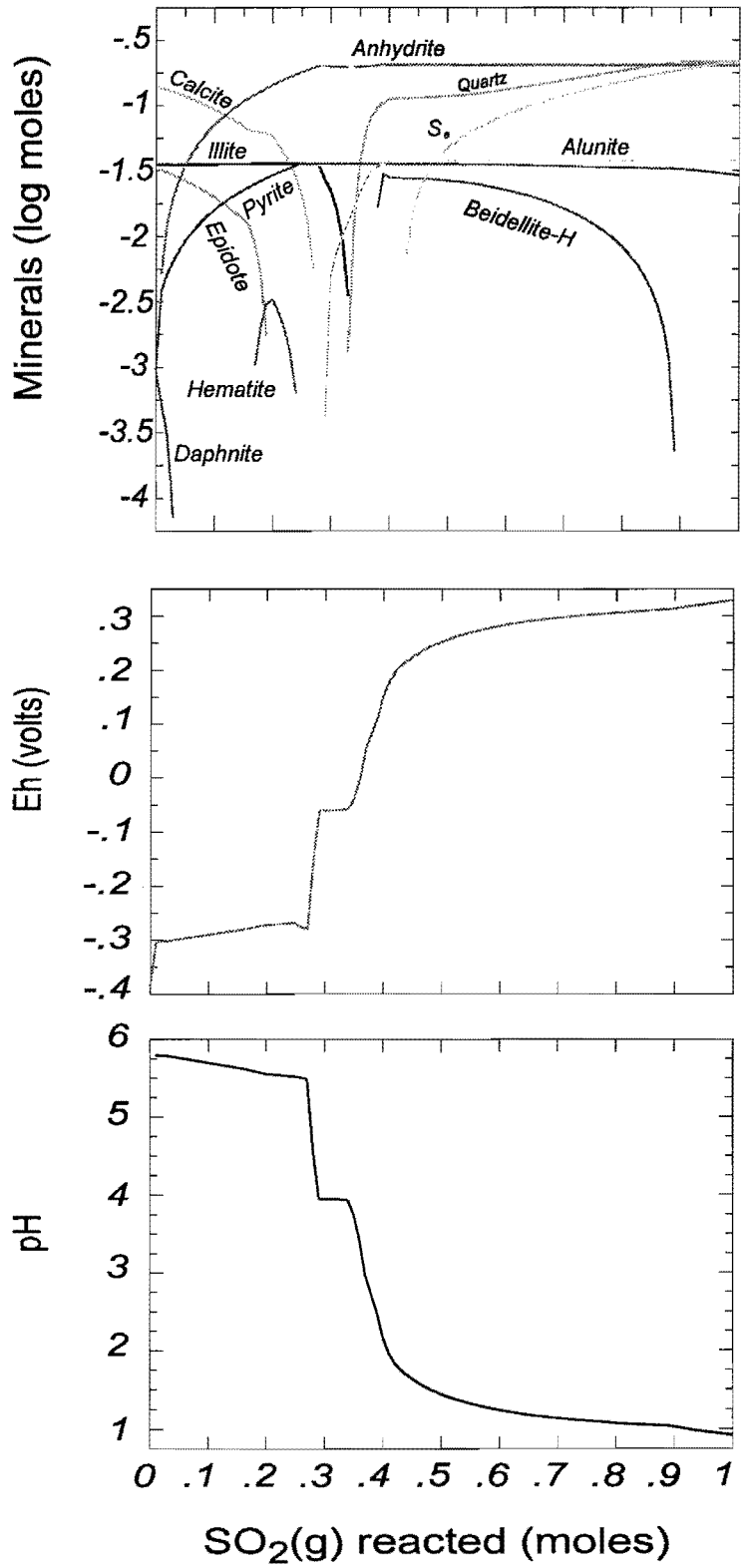
Output from the computer code REACT (Bethke, 1992; Fig. 4) shows the effects of titrating SO_2, the main oxidant in a volcanic volatile gas stream, into a reservoir fluid which is here represented by a discharge from Kawerau well KA21. In this case, the chemical system comprised of 1 kg of geothermal fluid which is saturated with respect to quartz at its equilibrium temperature of 273 °C, and is equilibrated with $5cm^3$ each of epidote, illite, and calcite prior to the titration of 1 mole of SO_2.

Early in the reaction sequence, calcite and epidote are replaced with anhydrite and pyrite respectively, and hematite becomes a stable phase at the expense of epidote. Calcite dissolution buffers the solution pH over the early stages of the reaction, but once totally dissolved, pH abruptly falls to the point where alunite saturates, and the assemblage alunite-illite is able to momentarily buffer the solution at approximately pH=4. On disappearance of illite, pH again sharply declines until a more protonated clay phase (in this case beidellite-H) saturates. Solution Eh increases only slowly at first, but after the last of the ferric iron phases dissolves, system Eh is dictated total by sulfur chemistry.

This single simulation provides only a snapshot of the conditions extant along fracture pathways extending from the magma conduit through which the Onepu Domes were extruded. However, the methodology allows for much wider evaluation of the

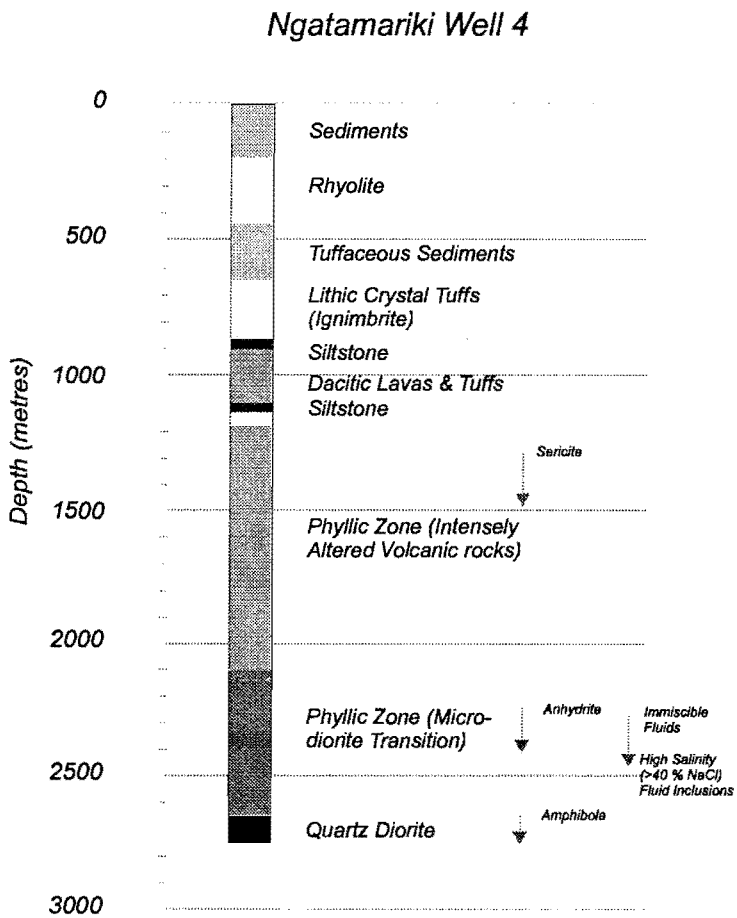
sensitivity of the system to various reservoir processes. For example, it provides the basis for development of 1 dimensional reactive transport modelling of such systems, and it can be developed to predict such parameters as the corrosivity of fluids in such environments.

Fig. 4. Reaction path model of the effects of magmatic SO_2 input into the Kawerau hydrothermal reservoir. Model is run at 273 °C.



The other TVZ hydrothermal system that presently exhibits an obvious magmatic connection is located at Ngatamariki (Fig. 1). Here, a quartz diorite pluton was intersected at relatively shallow depth (2200 m, Fig. 5). $^{40}Ar/^{39}Ar$ dating of hornblende phenocrysts in the pluton (at 400 ka) indicate that the pluton does not appear to be a present day heat source for the system. However, extensive hydrothermal alteration associated with the intrusive bears close resemblance to that found in porphyry copper deposits, and demonstrates that there was a significant magma hydrothermal interaction in the system.

Fig. 5. Stratigraphic section of Ngatamariki well NM-4.



An extensive zone of phyllic alteration some 100 m thick envelopes the quench margins of the pluton, and is characterised by coarsely crystalline sericite, quartz and pyrite alteration. Within the microdiorite - volcanic transition zone, veins of anhydrite and quartz ± sericite are prevalent, but there is a later overprinting by an assemblage consisting of quartz, wairakite, calcite and chlorite with lesser epidote.

The earlier quartz veins contain fluid inclusions indicative of fluid immiscibility in the precipitating hydrothermal fluid. One population of low salinity inclusions homogenise in the vapour phase, and is interspersed amongst a group of high salinity inclusions (halite + sylvite bearing) which homogenise in the liquid phase. Homogenisation temperatures are > 400 °C, and bulk salinities > 40 wt. % NaCl equivalent.

A work plan including petrology, mineral chemistry, mineral and fluid inclusion stable isotope analysis, and fluid (+ glass) inclusion studies is presently under way which will enable us to characterise the degassing history of the pluton. These data will

be used, as previously described, to ascertain the P-T-X conditions of the hydrothermal environment in and adjacent to the pluton, and thereby constrain thermodynamic and heat/mass transport models of this environment.

EXPLORING FOR PRESENT DAY HEAT SOURCES

One of the stated goals of this programme is to develop remote methodologies which will assist in locating present day magmatic heat sources which fuel the TVZ geothermal systems. Over the next six years, a sizable effort will go toward researching and applying new geochemical techniques, and refining existing electrical geophysical methods with the common aim of delineating the locations of shallowly seated magma bodies.

In years one and two, we are focussing geochemical efforts primarily on the Ohaaki system which is of interest because the discharge fluids from that system have two spatially distinct geochemical signatures, one possibly carrying a magmatic signature (Giggenbach, 1996). The approach will entail a comprehensive sampling of production discharges across the field, and application of all presently known geoindicators to the problem. In addition to the well established discriminating methods for gases and liquids (Giggenbach and Goguel, 1987), we will also analyse for stable isotopes of O, H, C, S, Cl, N and B, rare gas isotope signatures, and trace and ultra-trace non-volatile solutes. The data will be rigorously evaluated against "magmatic" signatures from active volcanoes in the TVZ, and correlation criteria thereby developed. In years three through six, these techniques will be applied to the Kawerau system, while new methodologies involving rare earth elements and U-series disequilibrium will be developed on the well characterised Ohaaki system.

The deep (2-4 km) resistivity structure of the Ohaaki and Kawerau fields will be mapped using a variety of techniques. Emphasis will be placed on the eastern borefield at Ohaaki, and the area beneath the 1000 year old Mt Edgecumbe volcano at Kawerau, both of which are known for high temperatures and low permeabilities at depth. Multiple source DC dipole-bipole and TDEM surveys will be carried out in conjunction with natural source magneto-telluric (MT), controlled source MT and TEM soundings of these areas.

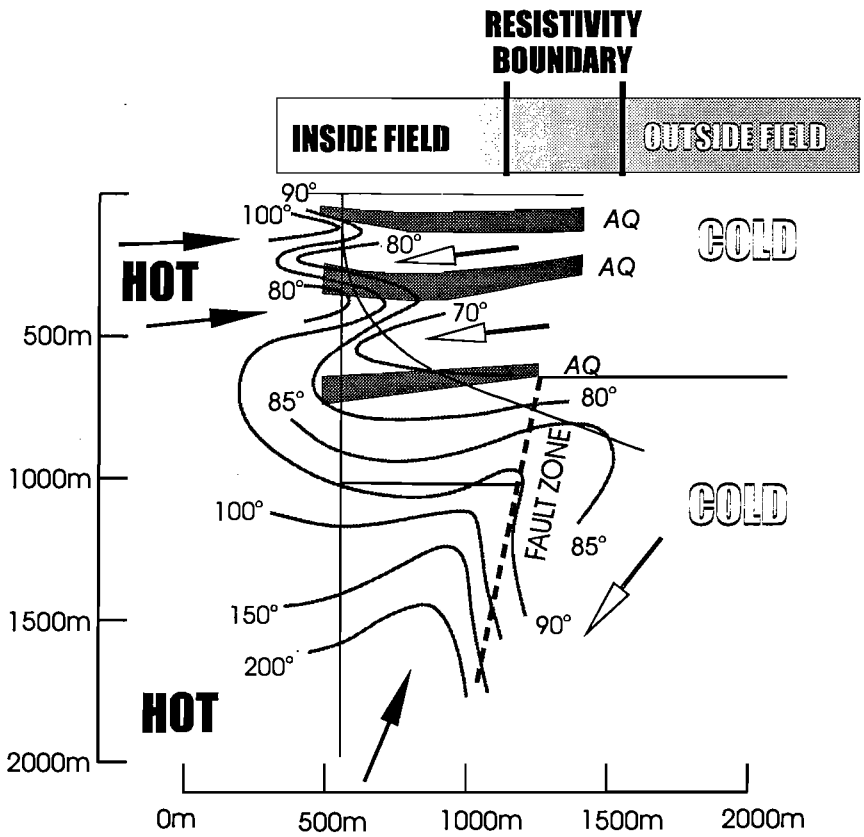
CHARACTERISATION OF THE TVZ FIELD BOUNDARIES: HOW DO THEY WORK?

Critically important to the development of models of heat and mass transfer in the heat source regions is a thorough understanding of the manner in which recharge fluids enter the convective domain. Consequently, a major effort is going toward quantifying the geological, geochemical and geophysical nature of the boundary regions in the three extensively drilled systems at Wairakei, Ohaaki and Kawerau.

Petrological and geochemical studies have commenced on cores, cuttings and fluids from 10 wells which have been sited close to the resistivity boundary of the Wairakei system. Two of these wells were deviated through the boundary, and finish in adjacent groundwater reservoirs. Temperature profiles for these deviated wells (eg. WK305, Fig. 6) are quite irregular, indicating that a complex system of counterflows

exist along the field margin. Initial findings from WK305 show that the well fluids are cool (< 95 °C), HCO_3^- rich, and saturated with respect to calcite. Alteration intensity declines rapidly across the boundary zone (over ≈ 100 m), and it appears that the zone has remained largely static through time. Calcite veinlets present in core recovered from the resistivity boundary proper indicate that this phase plays a role in controlling the permeability of the field margin.

Fig. 6. Temperature profile in Wairakei well WK305. AQ refers to "aquiclude".



Work planned for the next 18 months includes quantification of the rank and intensity of alteration across the boundary, analysis of fluid inclusions trapped in hydrothermal phases in this zone, and the development of reaction path models for the chemical processes operating in the zone constrained by well data. Predictive models of processes operating in the deeper boundary environments will then be attempted. Detailed re-evaluation of existing DC resistivity data in the vicinity of the marginal wells will be carried out, and will be augmented by tensor time-domain electromagnetic measurements (TDEM) across the boundary. Penetration depths of up to 3 km are feasible with the latter technique, which will provide insight into the deeper reservoir boundary environment.

CONCLUSIONS

Projects detailed above are effectively the core of the current research programme on Deep Geothermal Resources in the TVZ. Initial results are encouraging, and we feel confident that over the next six years we will advance our understanding not only of magma ambient environments, but provide insight into the bigger picture of how the large TVZ systems operate and evolve through time.

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