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Hotter and Deeper: New Zealand's Research Programme to Harness its Deep Geothermal Resources

Greg Bignall

Private Bag 2000, Wairakei Research Centre, GNS Science

g.bignall@gns.cri.nz

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ABSTRACT

New Zealand's conventional geothermal resources generate ~600 MWe (~10% total electricity generation), and are currently utilised to a depth of less than 3 km, where temperatures are up to 330°C. Utilisation of known geothermal resources could increase generation to 2,000 MWe, based on a conservative estimate of currently drillable and likely consentable systems in the Taupo Volcanic Zone (TVZ). Deep geothermal resources at depths of up to 5-7 km (where temperatures exceed 400°C), could exceed a potential of 10,000 MWe. This is close to the total New Zealand 2008 installed generating capacity.

A research programme has been established to better quantify New Zealand's deep geothermal resource potential. The research is lead by GNS Science, and includes specialist expertise from University of Auckland, Victoria University of Wellington, Industrial Research Ltd, and involves a network of international collaborations. The deep geothermal research, is funded by the New Zealand Government and supplemented with industry support, and is for 4 years. Two research themes are covered: (a) improved understanding of the deep structure and dynamics of the Taupo-Reporoa Basin. This is New Zealand's most intense area of deep-seated geothermal manifestations, and (b) greater understanding of the physical and chemical nature of the deep fluids and flow production pathways.

1. INTRODUCTION

New Zealand is endowed with some of the largest resources of 'conventional' high temperature, renewable geothermal energy (from 1-3 km deep, >240°C reservoirs). Increased use of indigenous geothermal resources will make a significant contribution to meeting New Zealand's 2% annual increase in electricity demand, using an economically-viable resource that has low greenhouse gas emissions. There is a possibility, however, of greater expansion through the development of untapped, deeper geothermal resources in the Taupo Volcanic Zone (TVZ).

The energy contained in hot rocks and fluids at 3-7 km depth in the TVZ is estimated to be >500 times the total gas field generation potential of New Zealand. Whilst temperatures (and available energy) increase with depth, ease of extraction decreases, since rocks at high pressures and temperatures become less porous, reducing fluid flow. At present, deep drilling and engineered geothermal system (EGS) development is expensive, and large investment is needed to reduce risk. A number of technical issues need to be addressed to delineate and develop EGS. However, if even a small percentage of the natural deep geothermal energy can be converted to electricity, New Zealand's energy security from renewable sources will be assured.

Research into deep geothermal energy utilisation is under way internationally, and New Zealand geoscientists are involved in several programmes. The New Zealand geothermal community, through its international networks and current research programmes (which currently leverages >$500k per year in-kind, industry co-funding) is well placed to apply accumulated science and technology to benefit New Zealand's geothermal energy developments.

A barrier to commercial development of deep geothermal resources is the ability to identify zones of permeability that could be tapped by deep drilling. In December 2008, the New Zealand Government, via the Foundation for Research Science and Technology (FRST) agreed to fund the GNS Science-led Deep Geothermal programme (*Harnessing New Zealand's Geothermal Resources: Hotter and Deeper*) at the level of $1.0M/y (+ GST), in a 4-year programme. The research programme involves specialists from GNS Science, University of Auckland, Victoria University of Wellington and Industrial Research Ltd. At its conclusion, it is intended that the study will have provided New Zealand's geothermal industry with the information they need to proceed with deep geothermal drilling and development with a high level of confidence. The programme is structured into two, multidisciplinary themes:

1.1 Exploration

The aim of this theme is to improve understanding of the deep structure and dynamics of the Taupo-Reporoa Basin (Figure 1), New Zealand's most intense area of geothermal resources. The programme will elucidate the geological framework (fault structure, lithology) of the Taupo-Reporoa Basin. The basin is a 'sweet spot' of conventional geothermal electricity generation, with ~1000 MWe operational or planned in the area. We will use geological and geophysical tools to infer the origin, structure and rifting-related dynamics of the basin. The area already has a significant magnetotelluric (MT) and seismic database, whilst drilling to 2-3 km and detailed resource modelling has been undertaken in several fields. A combined 4D geophysical/geological model will drive our collaboration which complements TVZ- and field-specific studies already under way.

1.2 Utilisation

We aim to enhance our understanding of the physical and chemical nature of deep TVZ fluids and their flow pathways, via geochemistry (experimental and field-based), fracture characterization and numerical modelling. At the temperatures and pressures anticipated to be encountered by future deep TVZ drilling, fluids are likely to be near the critical state of water. At these conditions, transport properties of fluids in the host rocks are poorly understood. Consequently, we need to understand:

- likely physical and chemical nature of the deep fluids;

- how fluids are transported below the geothermal system;
- rheology of the likely reservoir host rocks;
- nature of the fluid (fracture) pathways;
- how rock and fluid properties may impact on production;
- mechanics of developing engineered geothermal systems

We intend to research the physical and chemical nature of deep geothermal fluids (chemical composition, PVT, potential for mineral deposition), by a combination of experimental and field-based investigations. We also intend to resolve the nature of fluid flow by imaging present-day fractures (by acoustic formation borehole and fracture imaging, and laboratory testing of drill core) and numerical modelling fluid flow from the fractures into the well.

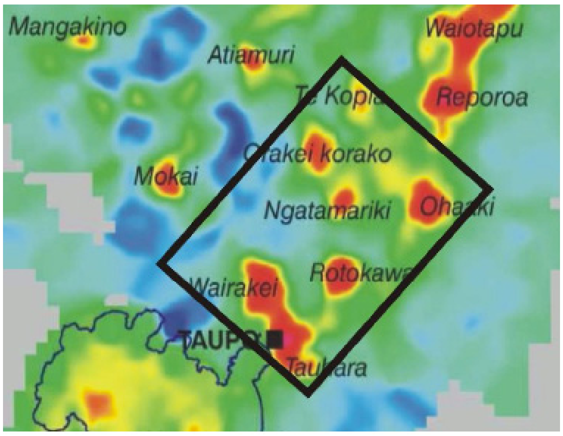

Figure 1: Proposed survey area for New Zealand's Deep Geothermal Research, and 'sweet spot' of existing geothermal electricity generation.

2. RESEARCH TEAM

The research programme involves New Zealand specialists from GNS Science (GNS), University of Auckland (UoA), Victoria University of Wellington (VUW) and Industrial Research Ltd. (IRL), with the science leaders being Greg Bignall (GNS; fluid-rock interaction, fracture characterisation), and Julie Rowland (Univ. Auckland, structural geology). Key researchers in the programmes also include: Stephen Bannister (GNS, seismic geophysics), Grant Caldwell (GNS, MT geophysics), Peter Malin and Eylon Shalev (UoA, seismic geophysics), Stephen Onacha (UoA, MT geophysics), Bruce Mountain and Bruce Christenson (GNS, geochemistry), Mike O'Sullivan (UoA, modeling), Warwick Kissling and John Burnell (IRL, modeling), Andrew Rae (GNS, geology), Mark Lawrence (GNS, borehole imaging) and Colin Wilson (VUW, volcanic stratigraphy, geochronology).

The research team has a well-sequenced path of tasks, projects and milestones to achieve project outcomes. Outcome delivery risk is mitigated by the strong track record of the research team, their global contacts, institutional support and long history of collaboration.

3. DETAILED METHODOLOGY

A number of scientific and technical issues need to be addressed to raise the level of confidence of the New Zealand geothermal industry, for them to drill deeper in the TVZ, i.e. to >4-7 km depth, and to demonstrate deep-seated, high-temperature engineered geothermal systems of the TVZ ***can*** be developed for their vast energy potential.

Key issues for catalysing deep geothermal development are:

- how do we image deep geothermal systems in the Taupo-Reporoa Basin? Where are the most prospective areas?
- we must develop predictive models for the behaviour of fluids, and mechanical rock properties likely to be encountered by deep drilling. How can we engineer the deep geothermal resources to facilitate energy utilisation?

To answer these questions, our integrated and collaborative scientific study will use state-of-the-art techniques in the disciplines of geophysics (deep MT imaging, seismic profiling), geology (4D structural interpretation, rock property testing, fracture characterisation), geochemistry (experimental and field-based), and reservoir engineering and mathematical modelling. In so doing, we aim to acquire the knowledge to tap and utilise the energy of New Zealand deep geothermal resources. This knowledge-base is essential for evaluating economic feasibility, increasing investment, and reducing and managing development risk.

Key themes in our research programme are designed to run for four years, with well defined interim achievement measures. Milestones occur in a network of activities, with a significant level of contribution between milestones (e.g. data contribution to models). The programme tackles issues not currently studied in New Zealand, but which need to be addressed to make deep geothermal resource utilisation a reality, and expands upon (but is complementary to) current GNS Science and University of Auckland geothermal programmes (C05X0704, UOAX0713), which focus research on "conventional" geothermal resources.

3.1 Integrated 4D Model of the Taupo-Reporoa Basin

The planned research will address the deep structure and dynamics in New Zealand's most intense area of deep-seated geothermal activity. The research will focus on the Taupo-Reporoa area. Linkages are proposed between geophysical and geological investigations to image the deep hydrothermal setting, and interpret any deep connectivity between active geothermal fields. By the end of the 4 year period, we aim to have prioritised well targets, to test hypotheses on fluid-flow pathways at 3-7 km depth.

A model for the geophysical (electromagnetic-MT/seismic) structure of the Taupo-Reporoa Basin will be generated to identify areas of permeability and fluid flow through (inferred low permeability) host rocks at depth, and identify structure(s) that may be targets of future deep drilling:

The integrated geophysical imaging plans to combine three geophysical techniques:

- a regional MT survey, to 3D image the electrical resistivity structure of the Taupo-Reporoa Basin to mid-crust levels (i.e., 3-7 km depth-range, where the rock is likely to be brittle, and capable of sustaining (fracture) permeability needed to extract its thermal energy).
- Surface passive source seismic analysis utilising rolling surface arrays that focus on selected areas in detail (station spacing of <1 km). The passive source survey will complement the MT surveys, and supplement data obtained from passive seismic borehole instrumentation.

GNS and UoA field surveys aim to acquire data from up to 200 new MT stations in the Taupo-Reporoa Basin, which will be combined with industry and TVZ-wide MT data held by GNS. A 3D resistivity image will be constructed, using data visualisation and resistivity modelling methods to (i) resolve the electrical resistivity structure at 3-7 km depth,

(ii) map the depth of the brittle-ductile transition, and (iii) identify potential targets for deep drilling.

New surface seismological data (~50 sites over 2 years) will be acquired, focusing on the Taupo-Reporoa Basin, to produce a 3D image of bulk seismic properties in the crust at 3-7 km. A 3D image of shear-wave seismic properties will be derived by inversion of broadband group and phase velocity maps (from dispersion measurements obtained from ambient noise), additionally determining bulk properties (Vp, Vp/Vs) using body wave tomography).

MT and seismological data will be combined to identify changes in physical properties (Poisson's ratio, rheology), develop a 3D image of the structure of this region of the mid-crust, and establish the present state of stress across the Taupo-Reporoa Basin to understand strain release patterns during faulting (and their inter-relationship to fracture opening and fluid flow, *if* hydrofracturing were to be part of any future deep geothermal development).

The major outcomes of the geological programme will be a: (i) predictive map of the Taupo-Reporoa Basin to 3-7 km depth; (ii) a time-series reconstruction of the basin; and (iii) model for the modern strain distributions across and along the basin. By understanding the geological character of the Taupo-Reporoa Basin, we will be better placed to deduce the structure and stratigraphy beneath the basin, and distribution and structure of deep-seated fractures, by:

- complementary FRST-funded research to date surface and subsurface volcanic rocks in the TVZ by $^{40}Ar/^{39}Ar$, U-Th disequilibrium and/or U-Pb techniques, which will provide age constraints on the geological evolution and rate of subsidence of the Taupo-Reporoa Basin.
- inferring basement geology and structural development of the Taupo-Reporoa Basin, in order to establish age and map data, which will be integrated to produce a (current) 3D model of the basin;
- investigating the influence of reservoir temperature (from well data, fluid inclusion data etc) and fluid chemistry on clay-chlorite chemistry in the hydrothermal setting, to resolve their influence on the interpretation of MT-resistivity data in TVZ geothermal systems;
- developing an integrated 4D image of the basement geological structure of the Taupo-Reporoa Basin to 7 km depth. The model will accommodate deep (geothermal) drillhole stratigraphy, surface geological mapping and age dating relationships, new regional geophysical survey data (models) and inferences from computer modelling of the TVZ hydrothermal system.

This objective also aims to model the rheology, permeability and chemical transport mechanisms (to below the brittle-ductile transition) in the Taupo-Reporoa Basin, with an overall numerical reservoir model that incorporates fracture characteristics, fluid flow and reservoir chemistry.

A transport model for the brittle-ductile transition zone will be developed to predict fluid, heat and chemical transport from a deep magma body into an overlying hydrothermal system. The model will be calibrated with inferred rates of heat/mass/chemical transport.

3.2. Geothermal Fluids and Deep Rocks in the TVZ

This theme focuses on the interrelated suite of features (e.g. fracture characteristics) and phenomena (e.g. fluid-rock interaction) important to the successful utilisation of deep-seated, high temperature geothermal resources, and will be studied here to resolve the controls on deep fluid flow. The research themes will address the properties of the fluids (PVT, chemical composition), how these fluids are transported through the deep crust (at 3-7 km depth), and the nature of the transporting paths in these deep zones where they approach the brittle-ductile transition.

The character of natural fractures networks in the high temperature geothermal environment is poorly known. Geological investigations will elucidate the fracture networks on a variety of scales (by analysis of geothermal cores, combined with data from rock property (rheological) testing and fluid-rock interaction experiments). Fracture (acoustic) imaging in geothermal wells, combined with rheological testing and fracture mapping, will resolve the (regional) stress regime in the Taupo-Reporoa Basin, and physical-chemical conditions conducive for development of fluid flow in naturally fractured, deep-seated rock masses.

In the future, permeability enhancement by hydro-fracturing may be required to develop deep geothermal systems in the TVZ. This will necessitate a combined fluid flow and rock mechanics model to design the hydro-fracturing programme. Application of the heat and mass transfer modelling code (e.g. flow simulator TOUGH2) and rock mechanics simulator (e.g. ABAQUS) will be used to predict the development of factures, and the fluid-rock reactions that may occur during production from a deep well. The work would be linked with geophysical observations to show the fracture cluster in the field setting. Modelling experiments may be carried out using CHEM-TOUGH or TOUGH-REACT to study the interaction between fracture flow (natural and artificial) and effects of chemical action.

An integrated field and laboratory study of fluid-rock interactions at high pressure-temperature (near-critical, or supercritical) conditions will be undertaken, as changes in rock properties impact on rock porosity, fracture permeability and well productivity. Hydrothermal experiments will utilise a custom-designed rocking autoclave system, with linked flow-through reactor, and focus on silica behaviour, thermodynamic stability of metal complexes and other alteration mineral assemblages. This will be undertaken as part of an international collaboration with researchers in Germany, Japan, and elsewhere, and via linkages with EGS drilling projects.

GNS Science has a key role characterising the nature of (supercritical) reservoir fluids in the Iceland Deep Drilling Project, which will provide insights into the nature of fluids that may be encountered by deep drilling in the TVZ. Fluid sampling will be undertaken at geothermal fields within the Taupo-Reporoa Basin, with chemical and isotopic tools used to identify the nature and location of heat source(s), and reactive transport capability. Building on collaboration with international EGS programmes, the application of new tracer tools for fluid flow monitoring and fracture characterisation will be assessed for New Zealand deep geothermal conditions.

4. TIMETABLE

At this stage (June, 2009), the details of the collaborative, 4-year, New Zealand Government supported, Deep Geothermal programme (*Harnessing New Zealand's Geothermal Resources: Hotter and Deeper*) are still being finalized, these include the official start-date for the research programme, and some budget details. However, it is envisaged the research programme will be underway early in the 2009-2010 financial year (after 1 July, 2009), and that the objectives of the programme, and progress to date will be reported, on at the WGC 2010 meeting in Bali, Indonesia.