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Towards a New Zealand Heat Flow Model

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ABSTRACT

A key part of expanding geothermal energy use outside regions with obvious surface expression, is developing a good understanding of the crustal thermal structure. However, the crustal temperature distribution across much of New Zealand is not well known. Good quality crustal temperature measurements are sparse and unevenly distributed. Furthermore, New Zealand's heat flow regime is complex with strong influences from fluid advection and convection, as well as transient processes (e.g., recent sedimentation and erosion) related to a relatively young and highly tectonic landmass. Predicting crustal temperatures is further limited due to the lack of good data on thermal properties of crustal rocks. We are developing a national temperature map using a 1D transient heat flow modelling approach. To support the model, we have established thermal properties measurement capability and are using measurements in conjunction with geochemical and mineralogical data to determine thermal properties. This paper presents progress towards the integration of a variety of datasets into a national temperature model for New Zealand.

1. INTRODUCTION

New Zealand has a long history of using geothermal energy to produce electricity, however, most developments to date have been restricted to known "hot" areas with clear surface features or geophysical expression (Bibby et al. 1995, Mclean et al. 2023). To help reduce New Zealand's carbon emissions to its target of net zero by 2050 (MFE 2023), there is an increased drive to make use of more of New Zealand's geothermal energy resources, which requires exploration away from previously developed fields. This will rely on a good understanding of New Zealand's crustal thermal structure, which is currently limited by the sparse distribution of direct temperature and heat flow measurements (e.g. Allis et al. 1998).

The transfer of heat through the crust occurs via thermal diffusion (conduction), and in areas where fluid flow is sufficiently rapid, fluid advection, or convection. Fluid transport via fluid convection or advection is important in areas with high permeability and/or temperature gradients, while in other areas diffusive processes dominate. In many parts of the world, geological processes are slow enough, or old enough that the heat flow regime can be treated as steady state. However, in geologically active regions, such as the Alpine Fault and Wanganui Basin of New Zealand, exhumation and/or subsidence can be so rapid that the thermal regime has not reached steady state causing significant and pervasive changes to the thermal structure (Shi et al. 1996, Allis et al. 1998, Kirkby et al. 2023). In this case, the transient component of the heat flow must be considered in modelling.

This paper presents progress toward a national heat flow map and crustal temperature model for New Zealand, where transient conditions are considered. In this paper, we provide a broad overview of the key controls on crustal temperatures and inputs used for modelling.

2. GEOLOGICAL BACKGROUND

New Zealand's thermal structure is in large part driven by its tectonic setting along a plate boundary fault between the Pacific and Australian plates (Allis et al. 1998). This boundary transitions from subduction in the north, at the Hikurangi Subduction Zone (and consequently high heat flow in the Taupo Volcanic Zone (TVZ) above the subducting slab) to transpression in the South Island along the Alpine Fault (Figure 1). Consequent high uplift rates on the Alpine Fault over the last 10 Ma (Walcott 1978, Kamp et al. 1989, Tippett and Kamp 1993, Sutherland 1996, Batt et al. 1999, Batt et al. 2004, Ring and Bernet 2010, Ring et al. 2019, Lang et al. 2020) drive high heat flow (Allis et al. 1998, Sutherland et al. 2017). Additional effects on the thermal regime include low heat flow in the rapidly subsiding Wanganui Basin, and Pliocene to Quaternary uplift and erosion causing elevated heat flow in parts of Taranaki (western North Island) (Allis et al. 1998).

METHOD

To calculate thermal profiles, we use 1D basin modelling software BM1D (Willett 1988, Armstrong 1996, Armstrong et al. 1996, Wood et al. 1998) which calculates the temperature and heat flow changes associated with transient and steady state diffusive processes. It takes into account variable sedimentation and uplift rates, porosity variations with depth, and temperature dependent thermal properties using the formulation of Sekiguchi (1984). The following sections summarize the key controls on the thermal structure, which are used as inputs in the model.

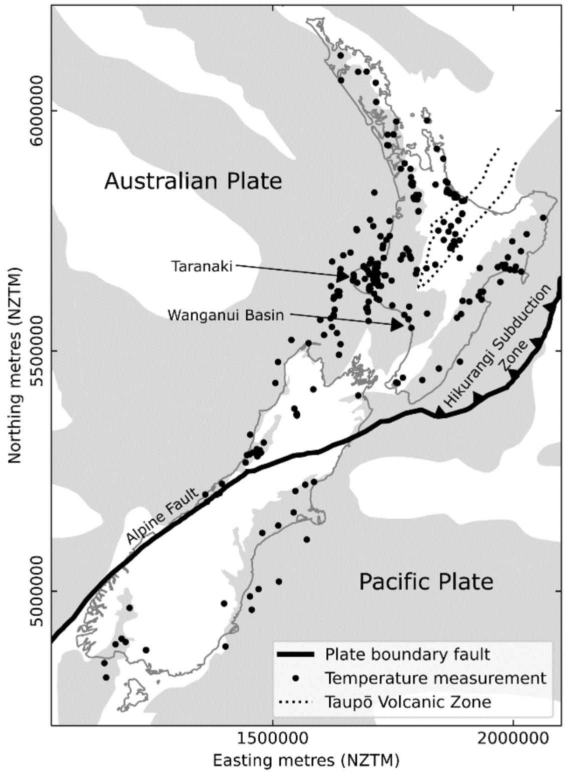

Figure 1. Location map showing features discussed in text and location of temperature measurements. Sedimentary basin cover shown in grey.

CONTROLS ON THERMAL STRUCTURE

Thermal properties

In a conductive heat flow regime, one of the key controls on temperatures at depth is crustal thermal conductivity and internal heat generation (Beardsmore and Cull 2001). Some key controls on rock thermal conductivity include mineralogic composition, porosity, pressure and temperature; with thermal conductivity generally decreasing with increasing porosity and increasing temperature, and increasing with increasing SiO_2 or quartz content and pressure (Funnell et al. 1996, Jennings et al. 2019, Norden et al. 2020). Internal heat generation is controlled by the concentration of radiogenic heat producing elements, uranium, thorium and potassium (Jessop 1990). Our model uses an exponential compaction model to determine porosity as a function with depth, then computes thermal conductivity and heat production as an average of porosity and grain thermal properties. Composition-based estimates of thermal conductivity of New Zealand basement terranes were determined from a combination of direct measurements using a Thermal Conductivity Scanner (Popov et al. 1999, Popov et al. 2016), and compositional data from across New Zealand (Kirkby et al. In prep) and used to estimate basement and sediment grain thermal properties.

Surface temperature

Surface temperature is particularly important to know when using shallow temperature measurements to calibrate a model, as the surface temperature in the model then determines the calibrated thermal gradient, and thus the heat flow. A present-day surface temperature grid for New Zealand was developed using mean annual 1m depth temperature measurements averaged over a period of at least 5 years, together with present day altitude, latitude and where applicable, sea depth (Kirkby et al. 2023). However, ground temperatures are affected not just by present day surface temperature but by past climates (Pollack and Huang 2000), as the change in temperature takes a period of time to penetrate the Earth's crust. This is a noticeable effect in our borehole temperature profiles, which suggest surface temperatures that are on average 2°C cooler than present day surface temperatures (based on extrapolation of profiles to the surface) compared to those from Kirkby et al. (2023) (Figure 2). This is consistent with a period of cooler temperatures during the Quaternary, compared to present day (Hornibrook 1992). For this reason, we model temperatures during the last 2 Ma as 2°C cooler than present day.

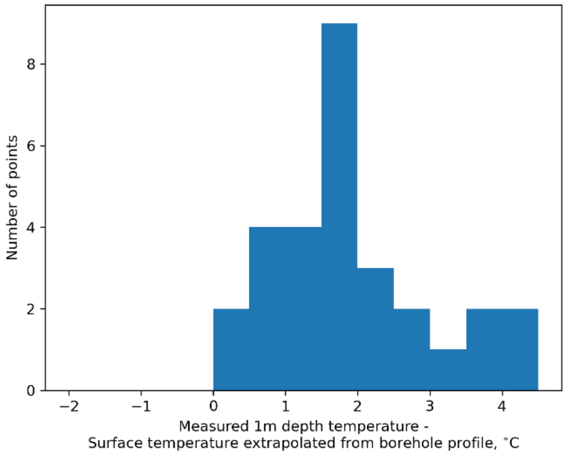

Figure 2. Difference between surface temperature derived from mean annual 1m depth temperatures and that extrapolated from borehole profiles.

Basin and exhumation history

In regions experiencing significant subsidence, understanding the distribution of sedimentary rocks is not only important in terms of controlling thermal property distribution, but the rate of deposition has a strong impact on heat flow. Rapid subsidence depresses heat flow, an effect that can extend through the crust (Kirkby et al. 2023). Likewise, rapid exhumation enhances the heat flow, and in New Zealand's Alpine Fault the effect is substantial (Shi et al. 1996, Sutherland et al. 2017, Kirkby et al. 2023).

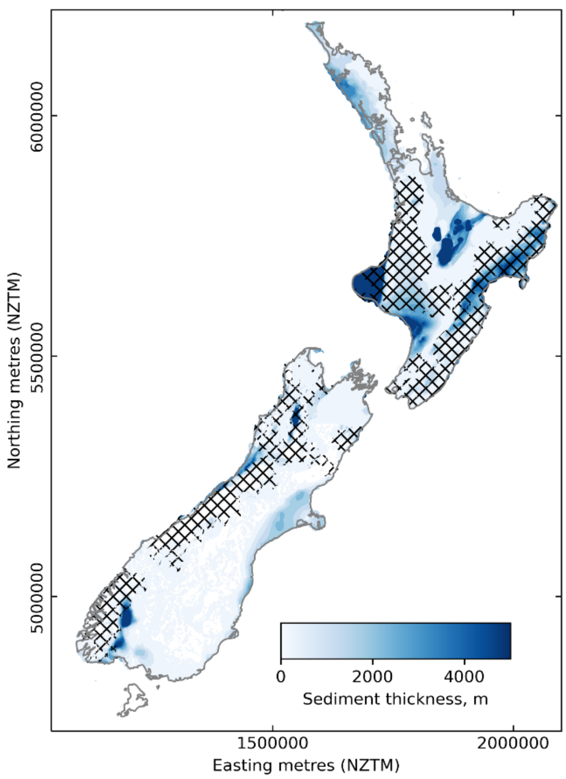

Figure 3. Sediment thickness and erosion model for New Zealand, merging data from multiple models on different scales (Nathan et al. 1986, Field et al. 1989, Edbrooke et al. 1994, Isaac et al. 1994, King and Thrasher 1996, Field et al. 1997, Armstrong et al. 1998, Pulford and Stern 2004, Wood and Stagpoole 2007, Bland et al. 2009, Alcaraz et al. 2012, Rawlinson 2014, White et al. 2015, Arnot and Bland 2016, Tschritter et al. 2016, Viskovic et al. 2016, Jiao et al. 2017, Sahoo et al. 2017, Arnot et al. 2018, Strogen et al. 2018). Areas with >500 m of erosion shown in black cross-hatching.

To account for the transient effects of sedimentation and erosion, our model is split into two layers representing sedimentation between 100 and 2 Ma, and either sedimentation or exhumation (depending on location) in the last 2 Ma. We compiled the distribution and timing of exhumation and sedimentation across New Zealand from multiple sources (Nathan et al. 1986, Field et al. 1989, Edbrooke et al. 1994, Isaac et al. 1994, King and Thrasher 1996, Field et al. 1997, Armstrong et al. 1998, Pulford and Stern 2004, Wood and Stagpoole 2007, Bland et al. 2009, Alcaraz et al. 2012, Rawlinson 2014, White et al. 2015, Arnot and Bland 2016, Tschritter et al. 2016, Viskovic et al. 2016, Jiao et al. 2017, Sahoo et al. 2017, Arnot et al. 2018, Strogen et al. 2018) to develop grids covering all of onshore New Zealand (Figure 3).

Basal heat flow

Basal heat flow directly impacts crustal temperature gradient so is a critical parameter in modelling. For our model, we determine basal heat flow based on calibration with direct borehole temperature measurements, with gridding guided by geological features likely to influence the heat flow, e.g. surface extent of the Alpine Fault, extent of the TVZ, orientation of the Hikurangi Subduction Zone. Rather than attempting to map heat flow variations within the TVZ, the TVZ was given uniformly high basal heat flow across its extent as mapped by (Wilson et al. 1995, Alcaraz et al. 2012).

PRELIMINARY RESULTS

Present day surface heat flow predicted by our model is shown in Figure 4. As expected, the model predicts high heat flow in the TVZ, caused by high basal heat flow associated with subduction, and along the Alpine Fault, associated with Quaternary exhumation. Other areas of higher than background heat flow include Northland, some areas of Taranaki, and the southwest and southeast of the South Island. Lower heat flows are predicted in the eastern North Island, Wanganui Basin, and central South Island. Work continues to refine the model and map not only heat flow but crustal temperatures at depth.

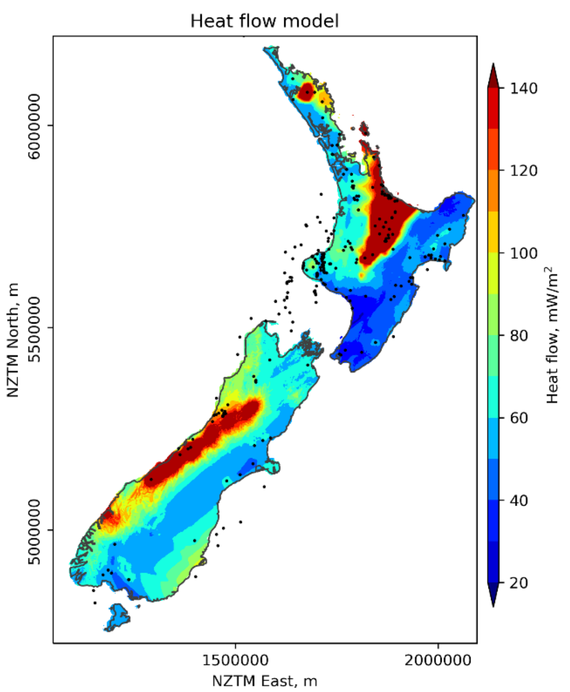

Figure 4. Preliminary predicted surface heat flow from modelling. Black dots show calibration points.

CONCLUSIONS

We are developing a crustal thermal model for New Zealand which will help guide future direct use of geothermal energy in New Zealand. Thermal structure in tectonically active regions is influenced by many factors, including those important in a steady state regime—basal heat flow and crustal thermal conductivity and heat production. Also included in our model are time dependent processes that influence heat flow, including geologically recent basin subsidence, exhumation, and climate change. These factors are vital to include in a tectonically active region such as New Zealand, and modelling these processes is a valuable part of understanding the thermal regime and therefore present-day crustal temperature.

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