Towards a national temperature model for New Zealand

Alison Kirkby[1], Rob Funnell[1], Phil Scadden[2], Matt Sagar[3] and Anya Seward[1]

[1]GNS Science, Wairakei Research Centre, 114 Karetoto Road, RD4, Taupō 3384

[2]GNS Science, Dunedin Research Centre, 764 Cumberland Street, Dunedin 9016

[3]GNS Science, Avalon Campus, 1 Fairway Drive, Avalon 5010

Private Bag 2000, Taupo 3352

a.kirkby@gns.cri.nz

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ABSTRACT

Knowledge of crustal temperature is important in expanding geothermal energy use across New Zealand, including low temperature direct use applications. However, crustal temperature distribution across much of New Zealand is not well known, despite New Zealand's extended history of developing geothermal resources. We are developing a national temperature map using a 1D transient heat flow model. To support the model, we have established thermal properties measurement capability and are using measurements from this in conjunction with geochemical and mineralogical data to estimate thermal properties. Development of other model inputs is ongoing. In this paper we discuss the thermal regime in three locations to demonstrate the impact of different processes occurring across the relatively young and tectonically active landmass of New Zealand. The Taupō Volcanic Zone is well known for extremely high heat output but the temperature gradient is strongly variable in this region due to fluid convection. Here, a conductive heat flow model will not be applicable, and so an alternative approach may be required. On the Alpine Fault, our transient 1D heat flow model estimates that the surface heat flow is enhanced by a factor of three due to Quaternary uplift and erosion; there are likely to be additional topographic and fluid flow effects for which the model does not account. In Wanganui, western North Island, our model predicts that the near surface heat flow is depressed by 20 mW/m^2 as a result of Plio–Pleistocene basin formation. In both regions, the effect of transient processes is present to depths of >20 km. Thus, Neogene processes leave a strong pervasive transient signal that extends to at least the mid crust.

1. INTRODUCTION

New Zealand has an extended history of developing geothermal resources for electricity generation, and to a lesser extent, direct use applications (Harvey et al. 2012, Carey et al. 2015, Climo et al. 2016). However, across much of the country, crustal temperature is poorly characterized. Knowledge of crustal temperatures is key for future development of geothermal resources in New Zealand, particularly in regions not traditionally recognized as "hot". Further, knowledge of crustal temperatures is also key for other applications, for example, to guide groundwater resource management, or developing a fault rupture depth model (Ellis et al. 2021).

High quality crustal temperature measurements are sparse and unevenly distributed, with distribution largely driven by the locations of historic petroleum exploration and groundwater monitoring bores. Furthermore, New Zealand's heat flow regime is complex with strong influences from fluid advection and convection (e.g., Bibby et al. 1995, Kissling et al. 2005, Sutherland et al. 2017, Pearson-Grant et al. 2021), and rock advection from sedimentation, uplift and erosion in the last ~20 Ma (e.g., Funnell et al. 1996, Allis et al. 1998, Sutherland et al. 2017). Thus, steady state heat flow modelling, which has commonly been applied in other parts of the world (e.g., Artemieva et al. 2001, Meixner et al. 2012, Mather et al. 2019) is not applicable to many parts of New Zealand. Predicting crustal temperatures is further limited due to a lack of good data on thermal properties of crustal rocks.

The most recently published heat flow map of New Zealand (Allis et al. 1998) was produced by contouring derived heat flow values from wells with temperature data available at the time and thermal property estimates. In some of the wells, a correction for surrounding topography was applied. The heat flow map provides a simplified representation of the thermal regime in New Zealand. The "background" surface heat flow is around 50-60 mW/m^2 with deviations from this largely due to Neogene tectonism (Allis et al. 1998).

This paper presents progress toward an updated national heat flow map and crustal temperature model, which will ultimately incorporate more recently collected temperature data as well as detailed information on rock properties, uplift and erosion, and sedimentary basin history. The model will be applied in a systematic way across New Zealand and calibrated to well temperature measurements to provide an updated surface heat flow map as well as estimates of crustal temperatures at a range of depths across New Zealand. In this paper, we present progress toward development of input grids for New Zealand, and present models for two locations, to illustrate the range of contrasting heat flow processes present in this tectonically active convergent plate margin (Norris et al. 1990). The first is the Southern Alps, in which exhumation, fluid advection as well as topography strongly enhance the heat flow. The second is the Wanganui Basin, North Island, where there has been rapid sedimentation during the Pliocene and Quaternary, which suppresses the heat flow. Finally, we discuss the Taupō Volcanic Zone (TVZ), for which fluid convection plays a strong role in the temperature distribution.

2. INPUT GRID DEVELOPMENT

2.2 Thermal properties

The coverage of existing thermal property data for New Zealand basement and cover rocks is currently very limited, making it difficult to determine representative values. To remedy this, GNS has commenced systematic measurement of representative rock samples from basement terranes across New Zealand (Mortimer 2004, Sagar et al. 2022). Samples were measured using both a divided bar apparatus (Benfield et al. 1939) and an optical thermal conductivity scanner (Popov et al. 1999).

The present coverage, 26 samples from the South Island, is not sufficient to provide representative values for New Zealand basement terranes. Therefore, we have utilized the substantial coverage of geochemical and mineralogical data contained in the PETLAB database (Strong et al. 2016) to estimate thermal properties (Figure 1). We assume that thermal conductivity in the upper crust is largely a function of the proportions of three end member minerals: Quartz (thermal conductivity of 7.69 W/mK at 20°C; Horai et al. 1969), olivine (5.06 W/mK; Kanamori et al. 1968), and "other" minerals (e.g. feldspars and amphibole, ~2 W/mK; Horai et al. 1969, Seipold 2001, Branlund et al. 2012, Xiong et al. 2021). We estimate quartz and olivine content using point count data (metasedimentary rocks) and use mesonorm calculations from bulk rock geochemistry data to estimate quartz content where applicable (i.e. only in diorite and granitoid rocks) using GCDKit (Janoušek et al. 2006). Thermal conductivities are estimated using a geometric mean of the proportions of each of these minerals, and then averaged to produce an estimate for each basement terrane (Figure 1b).

We compare thermal conductivities estimated using the mixing model above with measurements on the 18 basement terrane samples that have both mineralogy estimates and thermal conductivity measurements (Figure 1c). Overall, there is a reasonable match between the mixing model and the thermal conductivity scanner measurements, however, both the mixing model and the thermal conductivity scanner predict higher thermal conductivities on average than measured in the divided bar apparatus.

In a similar manner, internal radiogenic heat generation is estimated using U, Th and K concentrations (using formulation of Beardsmore et al. 2001) obtained from 5010 X-Ray Fluorescence (XRF) analyses of rock samples averaged to provide an estimate for each basement terrane (Figure 1a).

The pattern of estimated thermal conductivity and heat production for upper crustal basement rock samples across New Zealand can be described in terms of three regions. Along the western side of the South Island is predicted to have elevated heat production (>2 μW/m^3), which will increase the heat flow in these regions, and higher thermal conductivity (mostly >3 W/mK) (Figure 1a-b). The eastern terranes are estimated to have intermediate heat production and thermal conductivity. The terranes between these eastern and western regions, exposed mainly in the southern South Island and the northern and western North Island, tend to have lower heat production and thermal conductivity (generally <1 μW/m^3 and <2.6 W/mK).

2.2 Boundary conditions

Surface temperature and basal heat flow boundary conditions were applied to the models. The basal heat flow was initially assumed to be 43 mW/m^2 in both regions, based on a background surface heat flow of 60 mW/m^2 (Allis et al. 1998) minus a crustal contribution of 17 mW/m^2, assuming 1.2 μW/m^3 in the top 12 km (median value from the thermal property grid) and 0.17 μW/m^3 in the lower crust. Basal heat flow was then updated as required to match the data.

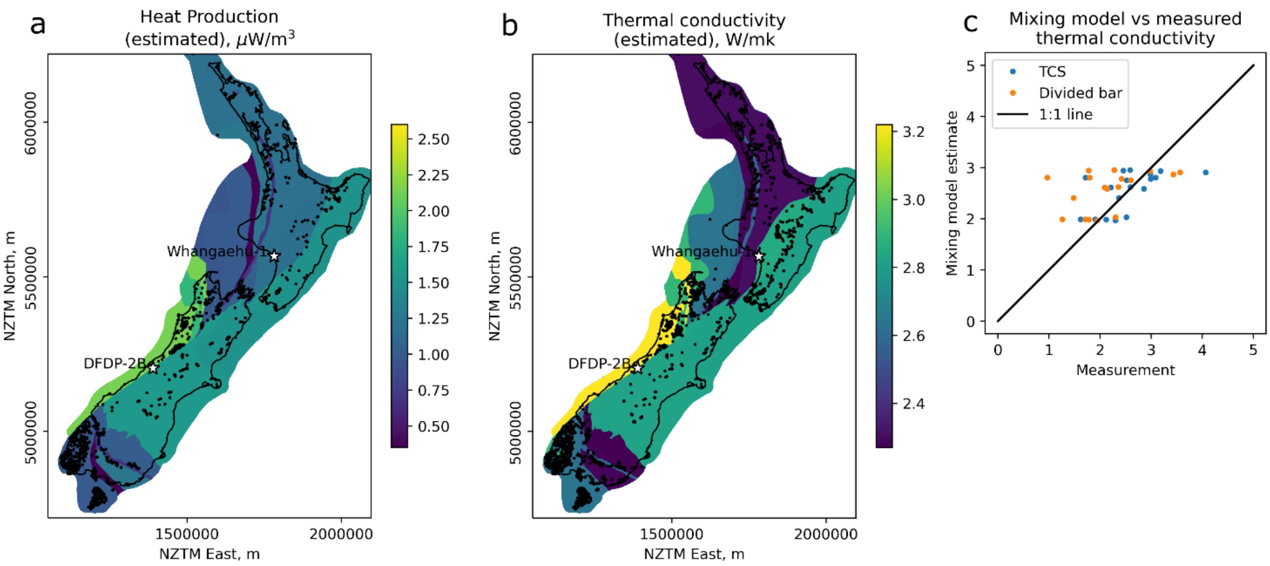

Figure 1: Estimated thermal properties for upper crustal basement rock samples across New Zealand based on geochemistry and mineralogy data in PETLAB (Strong et al. 2016). (a) radiogenic heat production estimated from concentrations of K, Th and U, (b) thermal conductivity estimated from quartz and olivine content, and (c) comparison of mixing model used in (b) and measured values in the Optical Thermal Conductivity Scanner (TCS) and divided bar apparatus. Points used to determine terrane properties shown in (a) and (b). Maps presented using New Zealand Transverse Mercator (NZTM) projection.

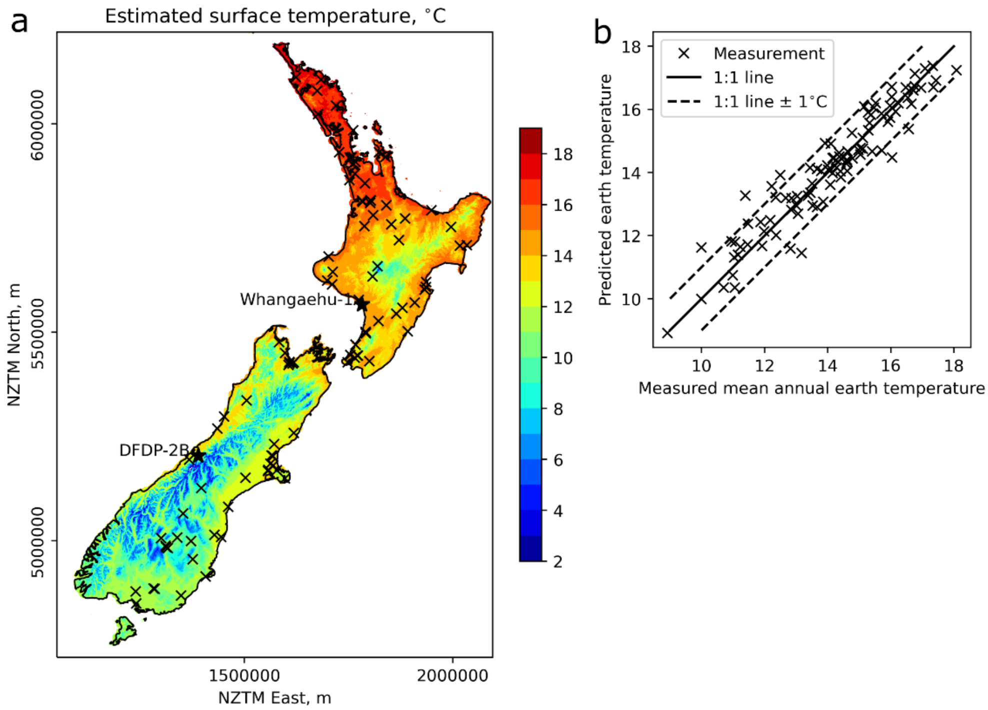

Figure 2: Surface temperature constraints to be used in 3D temperature and heat flow map of New Zealand. (a) estimated surface temperature across New Zealand, based on Equation 1, determined from fitting mean annual ground temperature measurements at 1 m depth as a linear function of altitude and latitude. (b) predicted as a function of measured earth temperatures. Co-ordinates are NZTM projection.

Due to the seasonal and diurnal variation in ground temperatures and the influence of rainfall, surface temperatures are best represented by temperatures in the top layer of rock for crustal thermal models (Beardsmore et al. 2001). Mean annual 1 m-depth ground temperature measurements were provided by NIWA for 46 locations across New Zealand, 17 in the South Island (Kevin McGill, pers. comm. 2006 [NIWA database]). Visually these show a relationship with both elevation and latitude, i.e. temperature decreases with increasing altitude and with decreasing latitude (i.e. increasing distance south from the equator), consistent with other regions globally that show a similar relationship between surface temperature and both latitude and altitude (Khandelwal et al., 2018; Wang et al., 2011).

To estimate ground temperature at other locations, we fit a plane to the temperature data as a function of altitude and latitude, that provides a quasi-linear relationship between both parameters:

$$T = 36.0 + 0.511Y - 4.72Z \qquad (1)$$

Where T is the temperature (°C), Y is the latitude in decimal degrees (e.g., -43.5°), and Z is the altitude in km. This predicts the surface temperature at the measurement points to within 1°C at most locations with measured earth temperatures, which is considered sufficient for crustal temperature modelling.

3. METHOD

We use a multi-one-dimensional finite element conductive heat flow modelling code BASSIM (Willett 1988, Armstrong 1996, Armstrong et al. 1996, Wood et al. 1998) to simulate the present-day heat flow and temperature profile. The code includes the thermal effects of variable sedimentation and erosion rates, spatially varying thermal properties, temperature dependence of thermal conductivity (Sekiguchi 1984), internal heat generation, and sediment compaction. Also possible to include, but not used for this analysis, are the thermal effects of crustal thinning and thickening, and volcanic intrusions.

We use the input grids developed in Section 2 to define thermal properties and boundary conditions for the two localities of interest. In addition, we use local estimates of sedimentation/erosion, and estimate the porosity as a function of depth, assuming a surface porosity ϕ_0 of 49% and a compaction factor d of 2500 (based on siltstone composition; Funnell et al. 1996) in the expression:

$$\phi = \phi_0 \exp\left(\frac{-z}{d}\right) \qquad (2)$$

Where ϕ is the estimated porosity at depth z (m).

4. RESULTS

4.1 Southern Alps

The Southern Alps in the South Island of New Zealand have experienced extremely rapid uplift and associated erosion over the last 10 Ma (Walcott 1978, Kamp et al. 1989, Tippett et al. 1993, Sutherland 1996, Batt Geoffrey et al. 1999, Batt et al. 2004, Ring et al. 2010, Ring et al. 2019, Lang et al. 2020), especially in the last 2 Ma (Jiao et al. 2017). When uplift and erosion occurs faster than the temperature profile can equilibrate, heat flow is enhanced, most strongly in the near surface but depending on the timing and duration of uplift, it can persist to middle or lower crustal levels. We illustrate this by showing a 1D temperature model at the

DFDP-2B borehole, which has had the temperature measured using a permanently installed fibre optic cable (Sutherland et al. 2017). It reaches a maximum temperature of 110°C at ~820 m depth; a temperature gradient of ~125°C/km (Sutherland et al. 2017). This general locality is estimated to have experienced ~7.8km erosion over the last 2 Ma (Jiao et al. 2017), which is incorporated into our 1D temperature model. We also run a quasi-steady state model, by running erosion from 520 to 500 Ma then letting the temperature profile equilibrate. The model has thermal properties determined from the thermal property grids (Section 2.1; 2.82 W/mK and 1.57 μW/m^3) in the upper crust, assumed to be 12 km thick prior to erosion, with thermal conductivity assumed to be temperature dependent according to the formula of Sekiguchi (1984). Lower crustal thermal conductivity was assumed to be independent of temperature at 2.2 W/mK based on a geometric mean of constituent minerals at ~375-575 °C (Touloukian et al. 1970, Seipold 2001, Branlund et al. 2012, Wang et al. 2014), with mineral composition as estimated by Guerri et al. (2015). Heat production was estimated at 0.17 μW/m^3 using recommended average lower crustal U, Th and K concentrations from Rudnick et al. (2003).

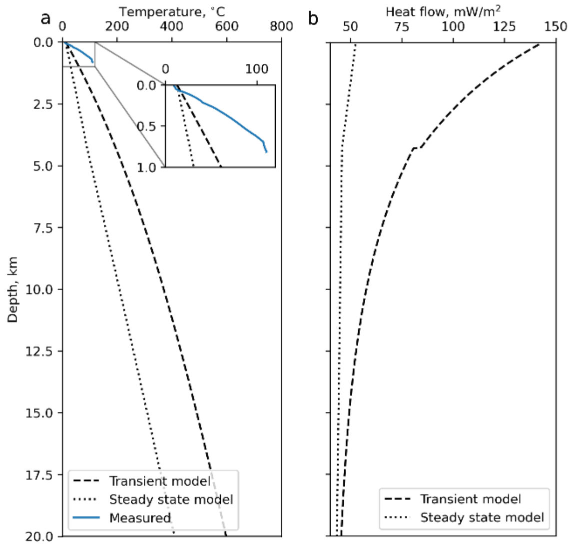

Figure 3: Results of 1D heat flow modelling at the DFDP-2B borehole in the Southern Alps. (a) temperature profile for a transient model with 7.8 km of erosion over the last 2 Ma, a steady state model, and the measured temperature. (b) predicted heat flow as a function of depth for the steady state and transient models.

Sutherland et al. (2017) modelled 3D heat transport via conduction as well as fluid and rock advection, in and around the DFDP-2B borehole, and concluded that rock advection and thermal diffusion were the key heat transport mechanisms at 240–740 m depth, but that fluid advection was also an important component affecting the local thermal regime. Our 1D transient heat flow model supports this finding. The temperature gradient (and heat flow) at the surface is increased by a factor of three when rock uplift is considered, relative to the steady state profile. At 3 km depth, the heat flow predicted by a transient model is still more than twice that predicted by steady state – it is not until a depth of >11 km before the transient heat flow is within 10 % of that expected from a steady state model. Thus, ongoing uplift on the Alpine Fault has a pervasive signal that persists to depth and is an important component of the of the thermal regime in the South Island of New Zealand.

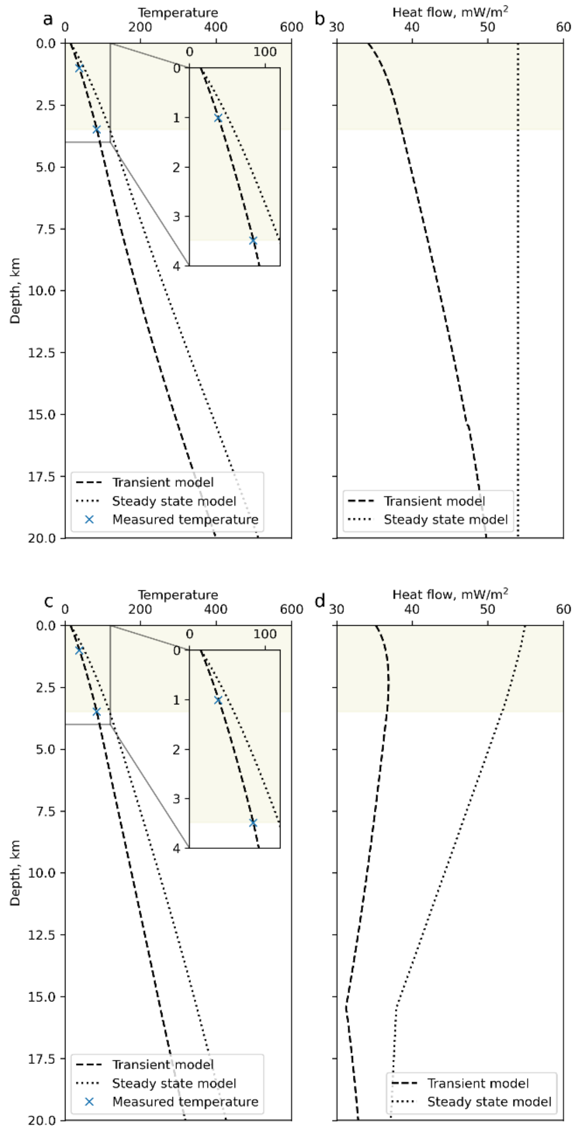

Figure 4: Results of 1D heat flow modelling at the Whangaehu-1 borehole in the Wanganui Basin. (a) temperature profile for a transient model with no heat production and 3.5 km of sedimentation over the last 5 Ma, a steady state model, and the measured temperature. (b) predicted heat flow as a function of depth for the steady state and transient models shown in (a). (c) temperature profile for a transient model with basement and sediment grain heat production equal to 1.17 μW/m3 and 3.5 km of sedimentation over the last 5 Ma, an equivalent steady state model, and the measured temperature. (d) predicted heat flow as a function of depth for model shown in (c).

Despite the strong influence of rock advection, it does not fully explain the temperature anomalies measured in boreholes near the Alpine Fault. At DFDP-2B, to match the measured temperature profile in a 1D conductive regime requires a basal heat flow of >100 mW/m^2, which is unrealistic for this part of New Zealand. Instead, it is likely that the shallow temperature and heat flow profiles are enhanced in the near surface as a result of topographic driven fluid flow near the Alpine Fault (as concluded by Sutherland et al. (2017)), as well as the topographic effect of being drilled in a valley, which can locally enhance heat flow by a factor of two (e.g., Jaeger 1965, Blackwell et al. 1980, Colgan et al. 2021). Furthermore, frictional heating may play a role (Shi et al. 1996).

4.2 Wanganui Basin

The Wanganui Basin contains up to 5 km of sedimentary rocks deposited over the last ~5 Ma (Kamp et al. 2004, Bland et al. 2009). Rapid sedimentation will depress the heat flow signal near the surface and, like erosion, can persist to greater depths in the crust. To illustrate this effect, we show a 1D model at the Whangaehu-1 well, where ~3.5 km of sediments were deposited during the Pliocene–Pleistocene (last ~5 Ma). We also run a quasi-steady state model as for DFDP-2B. The model used basement properties determined from the thermal property grids (Section 2.1; 2.85 W/mK and 1.17 µW/m^3), sediment grains were assumed to have the same thermal properties as basement with bulk thermal properties computed as a geometric mean of the sediment grain property and water using the compaction model described in Section 3. Both sediment and basement (upper crust) thermal conductivity were taken to be temperature dependent as in Section 4.1. The lower crust (>15.5km depth) was assigned a constant thermal conductivity of 2.2 W/mK and heat production 0.17 µW/m^3.

We first show an example with no crustal heat production to isolate the sedimentation signal from that of crustal heat production. To match the temperature measurements, a basal heat flow of 54 mW/m^2 is required – a steady state model requires a lower basal heat flow to match the temperature measurements. The heat flow is significantly depressed, reaching a minimum of 34 mW/m^2 at the surface. Similar to DFDP-2B, this signal is not simply a near-surface effect – at 10 km depth the heat flow is still only 44 mW/m^2.

Adding crustal heat production complicates the signal. To match the temperature in this case, a lower basal heat flow of 36 mW/m^2 is required. As a result, heat flow is nearly constant with depth, remaining between 31 and 37 mW/m^2, due to the competing effects of heat production and high sedimentation rates related to basin subsidence.

4.3 Taupō Volcanic Zone

The temperature profile in the TVZ is dominated by fluid convection, possibly down to 8 or 9 km depth (e.g., Bibby et al. 1995, Kissling 2004). Thus, the temperature structure within the TVZ is heterogeneous, with very low or close to zero gradients in regions of downflow and very high gradients in regions of upflow. Location of upflow may be controlled largely by topography, flow property distribution, depth of heat sources or a combination of all three (e.g., Kissling 2004, Pearson-Grant et al. 2021). Therefore, a conductive heat flow model is not applicable in this region. For a national map, a different approach will be required to estimate temperature in this region and others where heat transfer is dominated by fluid movement. This may be achieved by integrating results from other studies, effectively considering these regions separate from the rest of New Zealand.

5. CONCLUSION

New Zealand has a long history of developing geothermal resources, however, the temperature structure is poorly understood in many regions. The heat flow regime is strongly influenced by Neogene tectonism. For example, uplift and erosion on the Alpine Fault locally enhances the heat flow by a factor of three with further increases in the near surface likely resulting from fluid movement and topography. The heat flow enhancement due to uplift persists to mid-crustal depths, i.e., it is not simply a surface effect but a fundamental part of the heat flow signal. Conversely, sedimentation in the Wanganui Basin depresses heat flow down to depths of 20 km. Finally, heat flow in the TVZ is fundamentally affected by fluid circulation driven by elevated crustal temperatures associated with magmatism and crustal thinning.

We are working toward a national temperature map which will be valuable to identifying and developing future geothermal energy resources in New Zealand, particularly direct use. It may also be useful for a range of other applications, for example, in guiding groundwater resource management and in modelling crustal seismic velocities as well as predicting fault rupture depths. Progress so far includes establishment of a thermal properties laboratory, development of thermal property grids and a surface temperature map, and implementation of a method to predict temperature and heat flow with depth in this largely transient thermal regime. Additional work will include collating further temperature measurements to calibrate the model, refining thermal property grids, and development of grids of sedimentation over the last 100 Ma, and erosion over more recent time scales (2 Ma).

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