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3D Numerical Modelling of Heat Flow Across Heterogeneous Geology in South-East Australia

Ben R. Mather, Louis Moresi, Sandy Cruden, David Taylor

School of Earth Science, University of Melbourne, Parkville Victoria

brmather1@gmail.com

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ABSTRACT

Our knowledge of the thermal regime of the crust diminishes rapidly with depth. Seismic and magnetotelluric datasets are often plagued by inaccuracy that stems from poor knowledge of the composition of the crust and fluid alteration artefacts. Surface heat flow data, however, offers a reliable framework to constrain the thermal budget of the crust. The collection of 175 heat flow calculations in Victoria offers the highest resolution dataset available in Australia. A 1D interpolation of these data points reveals the heterogeneous nature of heat flow within Victoria. This, however, ignores important geological boundaries that may contribute to heat refraction. To address this, we have imported a 3D geological model of Victoria into Underworld, a finite element Lagrangian particle-in-cell program, to solve heat flow. We include depth-dependent thermal properties of the crust in our Underworld solutions, and forward model this against surface heat flow data. Our results show that incorporating geological structure substantially reduces the uncertainty for areas without direct heat flow measurements. Furthermore, there exists a zone of high heat flow between Bendigo and Ballarat, which correlates with region of low teleseismic velocity and high electrical conductivity that intrudes well into the mid crust. This region also coincides with a high spatial distribution of volcano eruption points that were active within the last 5 million years. Extrapolations of geotherms to depth within this anomalous zone highlights impossibly high temperatures at the base of the crust, in excess of 900˚C, which suggests a steady-state approach to crustal heat flow breaks down. This indicates that transient heat flow, arising from magma migration, dominates this part of the crust.

1. INTRODUCTION

Victoria is home to the greatest density of heat flow data inside Australia. 174 wells have been measured in Victoria accompanied by 664 conductivity measurements and 65 heat production analyses. The volume and accuracy of this dataset provides the framework for our forward modelling of temperature at the base of the crust. Our methodology uses 1D and 3D models that incorporates detailed information on the thermal properties of different lithologies at depth. Prior studies have used surface heat flow data to assist in assessing the geothermal potential of a region or for hydrocarbon exploration in the shallow crust. Our study extends far beyond conventional shallow targets and aims to map the entire thermal regime of the crust.

1.1 Major thermal events in Victorian geological history

Surface heat flow measurements provide a valuable insight into the thermal regime of the lithosphere because they record integrated information on time-dependent thermal processes within the crust (O'Neil et al. 2003). Victoria has been punctuated by several phases of crustal reworking and volcanism that is likely recorded in surface heat flow data. The Early Cretaceous saw the opening of the Otway and Gippsland Basins as Australia rifted from Antarctica (Miller et al., 2002). The sediments in these basins are efficient insulators (~ 1.8 W/mK) thus heat refracts around the deeper pockets of the basins towards the basement rocks in the North. In the Late Neogene a shift to Northwest-Southeast compression forced strike-slip movement along normal faults in the Otway Basin to cause decompression melting and volcanism (Lesti et al., 2008). The surface representation of this is the Newer Volcanics Province, a thin veneer of basalt that blankets 20,000 km2. The thermal perturbation of this event likely persists in Victorian crust today.

2. METHODOLOGY

We use Underworld, a finite element particle-in-cell Lagrangian program, to solve temperature at depth in 3D. The program has been thoroughly benchmarked to ensure accurate and reliable results. The geothermal plug-in to Underworld solves the steady-state heat equation which is derived from the standard heat equation:

$$\rho c_P \frac{\delta T}{\delta t} = \nabla \cdot \vec{Q} + H \tag{1}$$

For our 3D modelling we are only concerned with steady-state solutions, therefore the left side of Equation 1 becomes zero and we are left with the conduction equation,

$$0 = -\nabla \cdot \vec{Q} + H \tag{2}$$

where Q is the heat flux in three dimensions, and H is heat production. Our models of the crustal architecture, which are populated with thermal conductivity and heat production information, are forward-modelled against surface heat flow data to determine the thermal structure of Victorian crust. The model setup is a Cartesian box with a lower heat flux boundary condition and a constant surface temperature. The lower Neumann boundary condition is unknown, and is a parameter that we determine through forward modelling; the upper boundary condition is set to the average yearly surface temperature in Victoria.

2.1 Temperature-dependent conductivity

Thermal conductivity measured at room temperature does not remain constant with depth. We have applied a temperature-dependent conductivity function in order to approximate the in-situ conditions of the rock types in Victoria. There are two types of conduction: phonon, which dominates the crust and decreases the effective conductivity with temperature; and photon, which occurs mainly in the mantle and increases the effective conductivity. Our models are only concerned with the crust, therefore, we can ignore the effects of photon conduction. Temperature-dependent conductivity formulas usually take the form of

$$\lambda(T) = \frac{1}{A + BT} \tag{3}$$

where A and B are coefficients that depend on rock type (Seipold, 1998). One of these coefficients can be eliminated if a relationship between constants are found to leave the function purely dependent on room temperature conductivity. This method has proven popular with many authors (e.g. Seipold, 1998; Vosteen and Schellart, 2003; Kukkoken et al., 1998), however, applying functions like these produce unrealistically high temperatures in the deep crust of Victoria. Therefore, we have chosen two different coefficients for the upper and lower crust controlled by rock type, independent of room temperature conductivity. Victoria contains metasedimentary turbidites that have been metamorphosed to greenschist facies in the upper crust, and a mafic to ultramafic lower crust. Clauser and Hughens (1995) compared the temperature-dependent relationship for several rock types and revealed that sedimentary are highly temperature-dependent in the upper crust, whereas the conductivity of igneous rocks remain almost constant throughout the crust. Chapman (1986) used a two-layer approach to temperature-dependent conductivity in the crust. We apply the same approach to Victoria and use two different temperature corrections, b, for the upper and lower crust a constant depth correction, c, throughout the whole crust.

$$\lambda(T, z) = \lambda_0 \frac{1 + cz}{1 + bT} \tag{4}$$

2.2 Heterogeneous distribution of heat-producing elements

A uniform distribution of U, K, Th within a rock unit is often applied to thermal models of the crust. In cratonic lithosphere this is often not the case, here heat-producing elements are concentrated into an upper radiogenic layer leaving a lower depleted layer. The amount of differentiation varies with locality, however, Proterozoic crust in Victoria is assumed to bear a radiogenic to depleted ratio of 2.4:1 as derived from its Gawler Craton counterpart (Michaut et al., 2010). We use the exponential model from Sandiford et al. (1998) to characterise the vertical distribution of heat-producing elements in Proterozoic crust:

$$H(z) = H_i exp\left(\frac{-(z - z_i)^2}{hz_r^2}\right) \tag{5}$$

where the maximum heat production, Hi, decreases with depth, z, depending on the spread of the function, hzr, in metres. The effect of incorporating a heat production that diminishes with depth reduces temperature at the Moho.

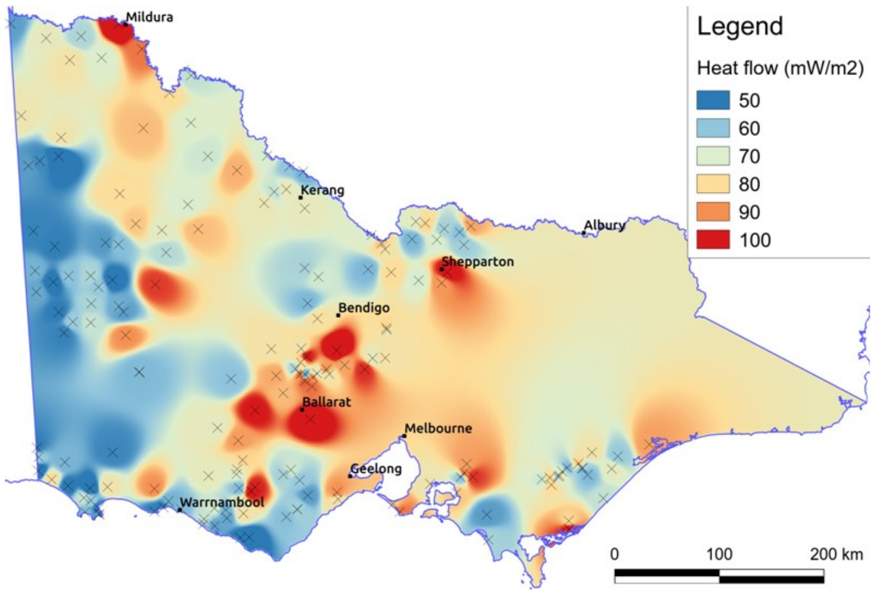

Figure 1: Interpolated surface heat flow data points, denoted by a cross, using inverse-distance weighting. Anomalous heat flow measurements exist between Bendigo and Ballarat.

3. RESULTS

1D heat flow measurements suffer where there are areas of poor coverage. An interpolation between points offer a first order approximation of heat flow without data, however, it is completely unconstrained. It is possible to infer heat flow at other locations by adding geological complexity to 3D models. Heat refraction between laterally heterogeneous rock units explains a lot of the variation in surface heat flow measurements especially North of the Otway and Gippsland Basins. However, a band of anomalously high heat flow is situated between Bendigo and Ballarat that cannot be explained in our purely conductive models. 1D extrapolations of temperature to depth reveal impossibly high Moho temperatures in excess of 900°C. This would cause mid-crustal melting, which is not occurring, thus heat transfer in this location must be transient.

3.1 Heat flow variation across Victoria

The new heat flow map of Victoria contains a large scatter of values, sometimes independent of geological province (Figure 1). In sedimentary basins at the southern margin of Australia there is extreme variation due to the lensing and thickening of highly insulating material. Further North the heat flow variation is less compared to similar distance scales in sedimentary basins, however, there is still significant heat flow scatter throughout each geological province.

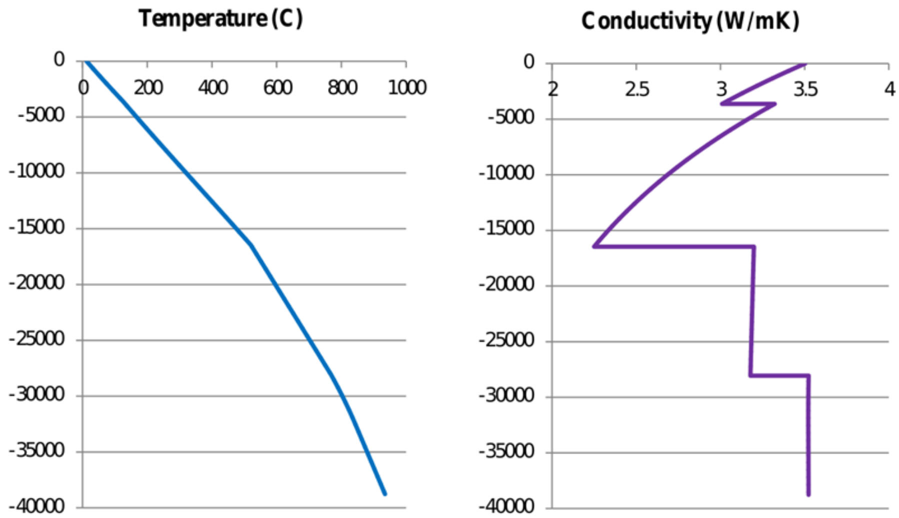

Figure 2: Geotherm through the anomalous zone between Bendigo and Ballarat, with its associated conductivity profile.

3.2 Magma migration in the crust

Steady-state models reveal impossibly high Moho temperatures beneath the surface heat flow anomaly between Bendigo and Ballarat in excess of 900°C (Figure 2). Surface heat flow can record thermal events that occurred millions of years ago. We use a finite difference numerical method to the thermal diffusion equation (Equation 1) to attempt to understand the latent heat in the crust that may perturb the geotherm. Information on the ages of eruptions and the major fault pathways help to constrain thermal pulses in the crust (Figure 3).

Multiple injections of magma at a fixed point and time in the crust have a time delay before any observations are made at the surface. The placement of the temperature pulse in the crust drastically changes the amount of time it takes to diffuse through the crust. Multiple temperature pulses create a cumulative effect on the surface heat flow, while leaving the basal heat flow relatively unchanged (Figure 4). This phenomenon can be used to explain the anomalous heat flow zone between Bendigo and Ballarat.

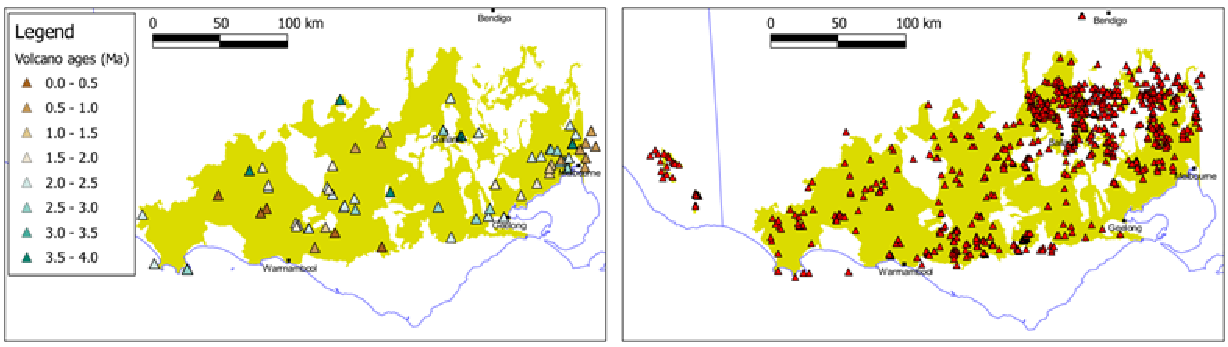

Figure 3: Aerial extent of the Newer Volcanics Province overlain with the ages of eruptions from geochemical analyses (left) and the spatial distribution of eruption centres (right)

4. CONCLUSION

The collection of 175 heat flow calculations in Victoria offers the highest resolution dataset available in Australia. A 1D interpolation of these data points reveals the heterogeneous nature of heat flow within Victoria. There exists a zone of high heat flow between Bendigo and Ballarat, which correlates with region of low teleseismic velocity and high electrical conductivity that intrudes well into the mid crust. This region coincides with a high spatial distribution of volcano eruption points that were active within the last 5 million years. Extrapolations of geotherms to depth within this anomalous zone highlights impossibly high temperatures at the base of the crust, in excess of 900˚C, which suggests a steady-state approach to crustal heat flow breaks down. This indicates that transient heat flow, arising from magma migration, dominates this part of the crust.

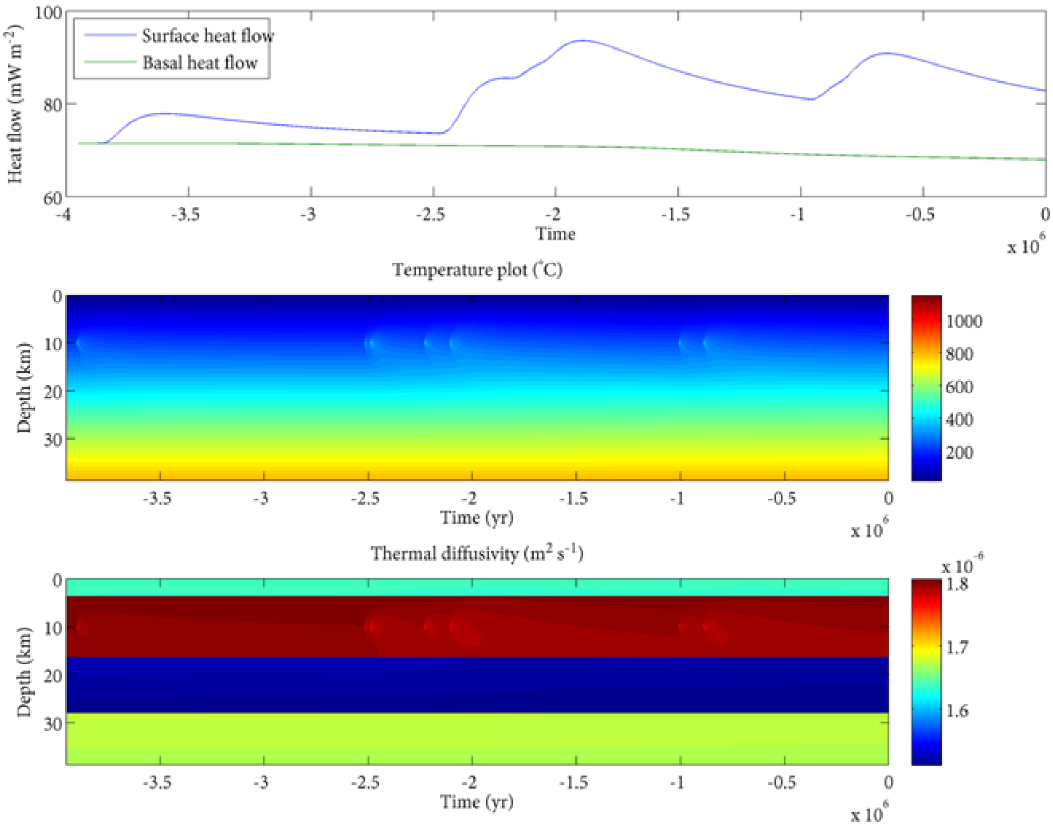

Figure 4: Finite difference model to the diffusion equation using forward time-stepping. A series of temperature pulses are introduced at times that correspond to the age of volcanic eruptions within the anomalous zone between Bendigo and Ballarat.

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