Thermal thinking: optimal targeting for Australian geothermal explorers

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Introduction

The two foremost criteria that define the viability of a potential geothermal reservoir are: the highest temperature at the shallowest depth, and sustainable geofluid flow rates. In addressing the former, geothermal explorers face a difficult challenge; a challenge starting with scarce or inaccurate thermal datasets extracted mostly from shallow drillholes, and concluding with oversimplified interpretations and underconstrained thermal models.

In the absence of deep drilling, temperature predictions at a target depth of several kilometers require the extrapolation of thermal data obtained from boreholes typically a few hundred metres deep. Because an uncertainty of 1 ºC at a 100 m depth translates to an error of 40 ºC at 4,000 m, it is essential that thermal data from shallow drillholes, in particular heat flow, be well constrained. Often the analysis of heat flow is considered as a one-dimensional steady-state and purely conductive heat transfer problem. This simplified view ignores transient effects and spatial variations which arise from heat and fluid transport as well as the inherent three-dimensional heterogeneity and anisotropy of the geological subsurface. In this context our approach to the problem is to establish a more rigorous evaluation in assessing the nature and significance of primary data. We specifically explore the role of heat refraction and palaeoclimatic transients and its incidence on extrapolation methods. In certain circumstances primary data from shallow boreholes can be evaluated and adequately relied upon for extrapolation at target depth, independently of deep drilling. We propose conceptual models showing why heat refraction, heat insulation, rock anisotropy and palaeoclimate cannot be ignored and how consequently explorers can optimize their geothermal targets.

Keywords: Australia, Latrobe Valley, heat flow modelling, heat refraction, palaeoclimatic corrections, Enhanced Geothermal Systems (EGS), Hot Fractured Rocks (HFR), Hot Dry Rocks (HDR), Deeply Buried Sedimentary Aquifers (DBSA), Hot Sedimentary Aquifers (HSA).

Heat refraction

Because the geological subsurface is not a layer cake, heat refraction occurs due to thermal conductivity contrasts. This lateral variation in the thermal properties of rocks will always result in heat refraction effects and will invariably impact on shallow heat flow fields. When the thermal conductivity contrasts are large, the relationship between temperature at target depth and surface heat flow is complex and non-trivial to understand. For example buried 'insulators' will induce high temperatures at depth, below the insulator; yet will display a negative heat flow anomaly at the surface (Figure 1, Appendix). In the Latrobe Valley (Victoria's Gippsland Basin), the magnitude of the anomaly associated with buried coals is estimated to be – 40 mWm^{-2}, with an inversely correlated temperature anomaly of + 20-30 ºC. This instance highlights the necessity to elucidate the source of heat flow anomalies before they are used to extrapolate temperature to target depth. Furthermore it provides a stringent test with respect to the robustness of primary data obtained from shallow drillholes. If shallow boreholes do not record the anomaly associated with heat refraction, they cannot reflect purely conductive heat flow processes and are therefore of little use in constraining temperature at target depth by extrapolation methods.

Palaeoclimatic corrections

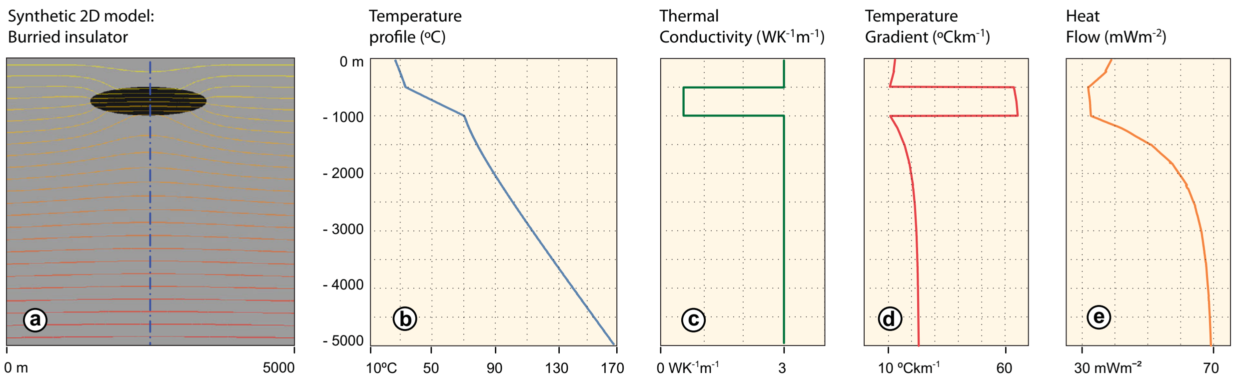
Palaeoclimatic variations over the Late Pleistocene have been extreme, with most proxy data indicating that surface temperatures along southern Australia are now some 6-8°C higher than at the height of the Last Glacial Maximum (LGM) some 18,000-20,000 years ago (Galloway 1965, Miller *et al*. 1997, Barrows *et al*. 2002, Hesse *et al*. 2004, Jouzel *et al*. 2007). Because surface temperatures are warmer now than in the past 100,000 years, surface heat has propagated into the shallow subsurface affecting an otherwise steady state-gradient. This means that temperature gradients are lower today than those of the LGM. This temperature anomaly needs to be accounted for in accurate heat flow modelling. The inversion of downhole temperature is arguably the only direct method that permits to determine palaeoclimatic ground surface temperatures histories from a few hundred years to 100,000 years (i.e. Hotchkiss and Ingersoll

1934, Benfield 1939, Birch 1948, Sass *et al*. 1971, Beck 1977, Clauser 1984, Chapman and Harris 1993, Pollack and Smerdon 2004, Beltrami *et al*. 2005, Rath and Mottaghy 2007). The use of the transient heat conduction equation (Carslaw and Jaeger 1959) with typical values of the thermal diffusivity of rocks (i.e.Touloukian *et al*. 1970, Seipold 1998, Beardsmore and Cull 2001, Mottaghy *et al*. 2008), show that excursions in ground surface temperature for 10, a 1,000 and a 100,000 years ago produce maximum temperature anomalies at depths of approximately 25, 250, 2,500 m respectively. A prescribed time-dependent boundary condition reveals that for every 1 °C of fluctuation at the ground surface corresponds a heat flow variation of approximately 1 mWm^{-2} at the depth of the anomaly maximum. Although the magnitude of this correction depends on whether the location of the borehole is ‘coastal’ or ‘intracontinental’, it has important implications for geothermal modelling since an uncorrected shallow heat flow estimate is most likely an underestimate.

Summary

Often the analysis of heat flow is considered as a one-dimensional, steady-state, purely conductive heat transfer problem, given constant boundary conditions. Because the geological subsurface is neither homogeneous nor isotropic, and because it is subject to various transients, one-dimensional steady-state modelling does not appear robust enough to develop well-constrained temperature or heat flow maps. This holds especially true when thermal data are extracted from shallow-depth drillholes. We propose through this contribution, an ongoing effort of the Geothermal Research Group at the School of Earth Sciences, University of Melbourne, a more rigorous evaluation of the nature and significance of shallow-depth thermal data. We develop theoretical and numerical models that demonstrate the importance of heat refraction and palaeoclimate variations through two-dimensional predictive heat flow modelling.

Appendix



Figures 1a, 1b, 1c, 1d, 1e: Synthetic 2D model (Fig. 1a) by finite element method, depicting a buried insulator placed between a depth of 500 m and a 1,000 m. Boundary conditions are a surface temperature of 17ºC (Fig. 1b) and a bottom heat flow of 70 mWm-2 at z = –10,000 m. The side boundaries are placed in the far-field and are mirror conditions. The thermal conductivities (Fig. 1c) are arbitrarily chosen at 0.5 Wm-1K-1 for the insulator, and 3.0 Wm-1K-1 for the rest of the domain. The thermal conductivity exerts a first order control on the gradient profile (Fig. 1d): to low thermal conductivities correspond large thermal gradients. The heat flow profile (Fig. 1e) demonstrates the large difference between the heat flow at the surface (30 to 40 mWm-2) and that at depth (70 mWm-2), a result of the heat refraction induced by the large thermal conductivity contrast.

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