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T. J. Rawling[a], M. Sandiford[a], G. R. Beardsmore[b], S. Quenette[c], S. H. Goyen[a] & B. Harrison[a]

[a] School of Earth Sciences, University of Melbourne, VIC 3010, Australia

[b] National ICT Australia, Parkville, VIC 3010, Australia

[c] School of Geosciences, Monash University, Wellington Rd., Clayton, VIC 3800, Australia

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Thermal insulation and geothermal targeting, with specific reference to coal-bearing basins

T. J. RAWLING[1]*, M. SANDIFORD[1], G. R. BEARDSMORE[2], S. QUENETTE[3], S. H. GOYEN[1] AND B. HARRISON[1]

[1]*School of Earth Sciences, University of Melbourne, VIC 3010, Australia.*
[2]*National ICT Australia, Parkville, VIC 3010, Australia.*
[3]*School of Geosciences, Monash University, Wellington Rd., Clayton, VIC 3800, Australia.*

Coal-bearing basins have increased economic potential for enhanced geothermal systems owing to thermal insulation provided by the coal and associated organic-rich sediments. In such insulation-dominated prospects, heat refraction effects associated with buried insulators can produce negative surface heat-flow anomalies in the most prospective areas. The Latrobe Valley in Victoria, Australia, is an archetypal coal basin. Using numerical simulations incorporating the coal geometries, we show that the Latrobe Valley coals might elevate the temperature of the rocks at 4 km depth by some 30–35°C relative to a 'base' condition with no coal. This effectively boosts the average geothermal gradient by about 30%, with a corresponding improvement in the economic case for geothermal energy in the Latrobe Valley.

KEYWORDS: geothermal, heat flow, energy, insulation, coal, targeting, Latrobe Valley, modelling.

INTRODUCTION

Companies exploring for non-volcanic geothermal resources in Australia have focused initial attention on regions with known or suspected elevated crustal heat flow or anomalously high crustal heat generation (e.g. Petratherm Ltd. 2004; Geothermal Resources Ltd. 2006; KUTh Energy Ltd. 2007; Torrens Energy Ltd. 2007). The companies have generally recognised high surface heat flow as a key indicator of an anomalous buried heat source. The companies have also generally recognised a requirement for 'an insulating cover of material' (Petratherm Ltd. 2004), 'a sufficient thickness of insulating sediments' (Geothermal Resources Ltd. 2006), 'a potentially good insulating blanket' (KUTh Energy Ltd. 2007), 'insulating sedimentary cover over the heat source' (Torrens Energy Ltd. 2007) and so forth, but efforts to quantify the properties and effects of the insulating blanket have typically been secondary to locating and quantifying high surface heat flow.

Elevated surface heat flow has been shown to be associated with relatively high concentrations of heat producing elements in crustal rocks beneath parts of Australia, most notably Proterozoic basement rocks such as A-type granites in central and south Australia (Neumann *et al.* 2000). Unfortunately, known geological terranes of this type are located long distances from existing electrical power infrastructure and markets. The most prospective 'hot rock' geothermal resources attributed to high heat-producing basement rocks are located in northeast South Australia, a remote, sparsely populated region with no access to existing transmission infrastructure. The minimum cost of connecting these remote projects to the national grid has been estimated on the order of $350 million (Geodynamics 2010).

Given that the goal of geothermal exploration is to identify bodies of rock with anomalously high *temperature*, rather than heat flow, a type of geothermal play providing elevated temperatures in response to thermal insulation (rather than high heat flow) presents possible benefits. Such geothermal plays are of particular relevance in coal-bearing basins, which are typically well endowed with an existing energy infrastructure.

The insulating effects of thick carbonaceous sequences have been known for some time (Pollack & Cercone 1994). This effect was originally postulated in response to the identification of over-mature hydrocarbon source rocks in regions of low heat flow with no obvious uplift or denudation but beneath thick carbonaceous sequences (Cercone & Pollack 1991; Cercone *et al.* 1996). Coal is by far the most insulating of all common sedimentary rocks, with a thermal conductivity only 10–20% of other typical sedimentary rocks (Beardsmore & Cull 2001). As a consequence, 100–200 m of coal provides the same effective thermal insulation as 1000 m of other typical sedimentary lithologies.

Heat, however, flows through the crust in three dimensions, preferentially along paths of least thermal resistance (greatest conductance). A significant thickness of coal represents a substantial barrier to vertical heat flow,

*Corresponding author: tim@modeltheearth.com

and, if a more conductive pathway exists, a portion of the heat from below will flow laterally around the coal. Understanding the effects of insulation on surface heat flow, particularly the role of heat refraction, is a critical prerequisite for designing effective exploration and geothermal targeting strategies in coal-bearing basins. This paper outlines some basic physical attributes of insulation-dominated geothermal plays, and provides a real-world example from the Latrobe Valley in Victoria, Australia.

ENGINEERED (OR ENHANCED) GEOTHERMAL SYSTEMS

Most of the world's geothermal power is currently produced from relatively high temperature, highly permeable fluid reservoirs in tectonically active settings. Production wells in such reservoirs can deliver natural steam to turbines for cost-effective power generation, but only within restricted geographic areas. There is increasing interest in methods that extend the geographic range of potential geothermal power production (Tester *et al.* 2006). These include power conversion technologies for generation from relatively low temperature resources, and engineering techniques for extracting thermal power from rocks of naturally low permeability. Projects employing the latter techniques are referred to as 'Engineered (or Enhanced) Geothermal Systems,' or 'EGS.'

In general terms, EGS refers to projects where the natural permeability of the geothermal system is artificially enhanced to allow fluid to pass through the rocks with sufficient ease to harvest heat at commercial rates. The production rate at which a specific project becomes commercial is specific to that project, but the common feature of all EGS projects is that the project will not achieve commerciality without artificial permeability enhancement (Goldstein *et al.* 2009).

Many different epithets have been connected to EGS projects, including 'hot dry rock,' 'hot wet rock,' 'hot fractured rock' and 'heat exchanger within insulator.' In reality, the majority of non-volcanic geothermal systems require some level of artificial flow enhancement, and so most projects lie somewhere on a continuum of EGS types depending on the geological setting and the nature and degree of enhancement needed to extract geothermal power (e.g. White & Williams 1975; Lund 2007).

One significant feature that distinguishes most EGS plays from 'conventional' geothermal settings is that the thermal regime typically reflects the natural conductive geothermal gradient within the crust, a consequence of their relatively low permeability. Fluids in permeable rocks subjected to high geothermal gradients often exceed the critical Rayleigh number at which buoyancy-driven flow, or 'free convection,' is triggered. This is the case in 'conventional' geothermal settings where hydrothermal convection systems develop within fractured volcanic rocks in the vicinity of cooling magma chambers, efficiently transporting heat from depth to shallow, easily accessible levels. Free convection is effectively stifled in low-permeability rocks, so heat transport is by conduction alone, and the thermal gradient is a function of heat flow and thermal conductivity.

In order to be prospective for economic development, the anticipated cost of drilling must be substantially lower than the value of the thermal energy extracted from an EGS project. In practice, that means that a key first-stage resource evaluation relies on screening for anomalous thermal gradients in the upper 3–5 km of the crust. For example, Torrens Energy Ltd. (2007) quoted minimum thermal gradients of 35–40°C/km averaged over the upper 5 km of the crust as an effective cutoff 'grade' for prospectivity.

The global average thermal gradient on continents is about 25°C/km. The most attractive EGS prospects in terms of thermal gradient are in areas with both elevated heat flow and thick insulating material. For example, Geodynamics Ltd's 'Habanero' EGS project near Innamincka in South Australia encountered granite in excess of 240°C at just over 4100 m depth (Geodynamics Ltd. 2012), or an average gradient exceeding 50°C/km. The high average gradient in the region is due to relatively high heat flow within relatively insulating, organic-rich sedimentary units (Beardsmore 2004).

Both conditions do not need to occur together to produce elevated thermal gradients. Thermal gradients might exceed average by at least 50% in areas with either significantly higher than average heat flow (continental average heat flow is around 65 mW/m^2, with regional variations from ~30 mW/m^2 to ~130 mW/m^2 in tectonically active settings; Beardsmore & Cull 2001) or significantly lower than average thermal conductivity (average thermal conductivity of the continental crust is around 2.7 W/mK, with variations from 0.5 to 8 W/mK for natural rock types). This allows for two end-member EGS play types in terms of thermal gradient:

(1) strata of normal thermal conductivity in regions of elevated heat flow ($>$ 90 mW/m^2), such as above or within a radioactive granite, and
(2) strata of much-lower-than-normal thermal conductivity (less than 2 W/mK on average) in regions of normal heat flow, such as beneath a thick succession of coals.

A fundamental difference in exploration strategy between these two play types relates to the surface heat-flow expression of the geothermal reservoir. In the former, the reservoir invariably coincides with a peak in the surface heat flow. However, in the latter, 'insulation-dominated geothermal systems,' heat-refraction effects tend to produce local surface heat-flow minima above the insulating bodies. Heat refraction also contributes to very substantial variations in vertical heat flow with depth that can render one dimension (1D) temperature projections from shallow heat-flow estimates grossly inaccurate. The remainder of this paper focuses on insulation-dominated geothermal systems.

EXPLORATION FOR INSULATION-DOMINATED GEOTHERMAL SYSTEMS

As explained above, thick insulating sequences provide an ideal precondition for elevated average thermal gradients. Insulation-dominated geothermal systems might also provide benefits with respect to the quality of potential reservoirs. With potential reservoir units at relatively shallow depth (compared with uninsulated locations), they might retain higher primary permeability because of reduced levels of compaction and diagenesis owing to shallower burial beneath less dense material. Diagenesis is the process of low-temperature mineralogical change within basin sediments after deposition, and commonly results in a reduction in primary porosity and permeability owing to recrystallisation and mineral precipitation. Higher pressure and temperature conditions tend to promote or speed up these textural changes.

Exploration for insulation-dominated geothermal systems requires careful interpretation of near-surface heat-flow data, especially when such data are derived from bore holes less than a few hundred metres deep. First, non-equilibrium effects associated with temperature measurement must be removed, and then the effects of any heat removal from groundwater flow in shallow aquifers must be accounted for. The general effect of low conductivity material on thermal gradient must then be understood, as well as the potential impact of heat refraction in three dimensions.

Insulation-dominated geothermal systems in 1D space

The impact of thermal conductivity variation on temperatures within the Earth is most simply illustrated in terms of a 1D model in which all heat flow is strictly vertical. In geological terms, such a situation is approximated by a relatively uniform, horizontally stratified sequence in which the horizontal extent of the strata is very much greater than the vertical thickness of the conducting regime. In reality, most geological settings involve some degree of heat refraction owing to lateral variations in thermal conductivity, and the effect of such variations is considered in detail in the next section.

In 1D steady-state conduction, the impact of a conductivity contrast on temperature profiles can be referenced against a standard conductivity, k_{ref}. For a fixed surface temperature boundary condition, the temperature anomaly at depth, z, induced by conductivity anomalies in the overlying strata is the product of the heat flow, q, and the depth integral of the differences between the reciprocal conductivities and the reciprocal of the standard conductivity:

$$\Delta T = -q \int_0^z \left(\frac{1}{k_{\mathrm{ref}}} - \frac{1}{k(z)} \right) \mathrm{d}z \qquad (1)$$

A layer of uniform, anomalous conductivity, k, and thickness, z, gives (e.g. Sandiford 1999):

$$\Delta T = -q \cdot z \cdot \left(\frac{1}{k_{\mathrm{ref}}} - \frac{1}{k} \right) \qquad (2)$$

Equation 2 provides a simple 'back of the envelope' estimation of the 'insulation potential' of any arbitrary layer relative to a standard conductivity for a given heat flow. For example, a cumulative thickness of 400 m of coal with $k = 0.5$ W/mK (average value incorporating higher conductivity interseam sediments over the 400 m thickness) would have an insulation potential of 48°C relative to a sequence with reference conductivity, $k_{\mathrm{ref}} = 2.6$ W/mK, and for a heat flow of 75 mW/m^2 (Figure 1). That is, temperatures below the coal would be about 48°C higher than the reference case.

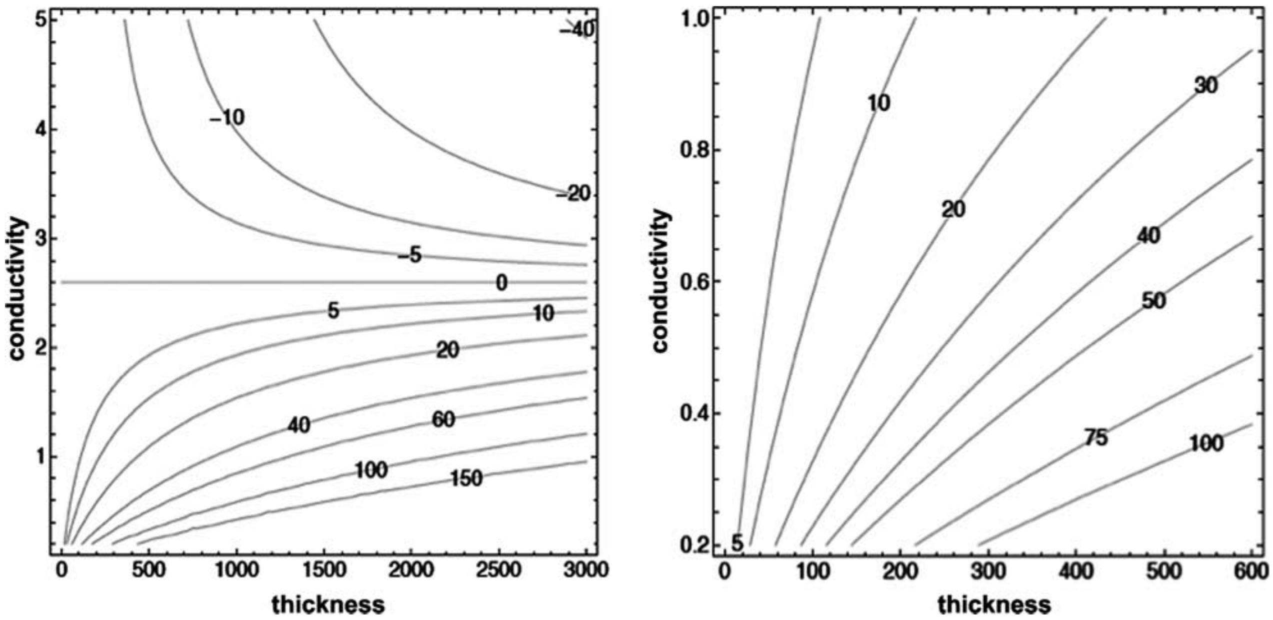

Figure 1 (a) Estimated insulation potential, or 1D-temperature anomalies, associated with a buried insulator/conductor of specified thickness, z, in a region with heat flow 75 mW/m^2, referenced against a standard conductivity (k_{ref}) of 2.6 W/mK. (b) Detail of (a) relevant to coal with a conductivity of 0.5 W/mK.

Insulation-dominated geothermal systems in multi-dimensional space

The thickness and lateral distribution of coal in a sedimentary basin are both controlled by primary depositional environments and subsequent folding and/or faulting, and can lead to extreme lateral and vertical variability in thermal conductivity. In these circumstances, heat refraction (that is, deviation from vertical heat flow) plays an important role in modulating the temperature field in the basin, and leads to surface patterns of heat flow that depart markedly from uniformity. For example, a confined thermal insulator, buried at depth and exposed to a uniform heat flow from below, produces a negative surface heat-flow anomaly directly above the insulator, while elevating temperatures below (Figure 2). In such settings, there is the paradoxical opportunity for prospective geothermal reservoirs associated with negative surface heat-flow anomalies. Below, we explore these issues using numerical models for confined buried insulators.

Figure 2 shows the generalised pattern of thermal anomalies produced by confined buried conductivity anomalies. The figure shows both an insulator (for example, a discrete deposit of coal) and a conductor (for example, a diapir of salt) embedded in a material of 'standard' conductivity, subject to constant temperature at the upper boundary, and a constant heat influx at the lower boundary.

In the case of the buried insulator, the steepening of vertical thermal gradients within the anomalous body is represented by isotherms being drawn towards the body from both above and below. The separation of isotherms above the body is representative of the lower geothermal gradient and reduced vertical component of heat flow. The local build-up of temperature beneath the anomaly induces a horizontal component of thermal gradient and lateral heat flow. Lateral heat flow diminishes the rate of vertical heat flow through the insulator to the surface. For a uniform heat influx at the lower boundary, this means a diminished surface heat flow immediately above the insulator, with slight positive heat-flow anomalies above the edges of the insulator. The buried conductor has the opposite impact, resulting in elevated surface heat flow above the body, slight negative heat-flow anomalies above the edges of the body and diminished temperature beneath.

An important insight from the generalised models in Figure 2 is the counter-intuitive relationship between surface heat-flow anomalies and temperature at depth in the presence of discrete bodies of anomalous thermal conductivity. To explore these matters more rigorously, and establish the controls on the effect and its magnitude, we employed a simple model for a confined conductivity anomaly where conductivity was expressed as a continuous variable in two-dimensional (2D) space, as described by Equation 3. Appendix 1 provides more details of the specific model parameters.

$$k_{xz} = k_{\mathrm{ref}} + (k - k_{\mathrm{ref}})\left(\exp\left(\frac{(z - z_i)^2}{h_z^2}\right)\exp\left(-\frac{x^2}{h_x^2}\right)\right) \quad (3)$$

In Equation 3, x is the horizontal ordinate and z is depth, k and k_{ref} are the characteristic conductivities of the anomaly and the reference material, z_i is the characteristic depth of the anomaly, and h_z and h_x are the characteristic height and width, respectively, of the anomaly.

We computed the thermal impact of an infinitely long package of insulating sediment confined in height and width within a reference package of sediment exposed to a uniform basal heat influx of 75 mW/m^2. We explored a set of models with $h_z = 400$ m, $k = 0.5$ W/mK, $k_{\mathrm{ref}} = 2.66$ W/mK, $z_i = 300$ m, and various values of h_x. Very high ratios of h_x to h_z approximate the 1D situation described by Equation 2. Results are displayed graphically in Figure 3a–d.

Figure 3a displays the modelled temperature anomalies as a function of depth (predicted for a vertical profile through the axis of the anomalous body and relative to a reference state with no anomalous body) owing to a confined insulator with the properties given above and values of h_x of 5 km, 10 km, 20 km, 50 km and 5000 km. The greatest value of h_x effectively approximates the 1D case and suggests maximum 'insulation potential' of about 46°C.

Figure 3b normalises the profiles from Figure 3a to show the proportion of the maximum 'insulation potential' that might be expected beneath insulating bodies of finite width. The graphs show that the insulation effect of a shallow conductivity anomaly depends strongly on the width of the anomaly. In the modelled scenario, the insulation effect at 4 km depth beneath the centre of the anomaly drops from around 70% of the 'ideal' maximum for a 20 km wide anomaly to around 30% of the 'ideal' maximum for a 5 km wide anomaly.

Figure 3c illustrates the predicted surface heat flow for the same set of models described above, along a horizontal profile from the axis of symmetry of the conductivity anomaly. Maximum negative surface heat-flow anomalies are predicted at the axis of symmetry, while slight positive anomalies are predicted at the edge of the insulating body, caused by the refraction of heat from beneath the insulating layer. The amplitude of both positive and negative anomalies increases with the inverse of the width of the insulating body (that is, with $1/h_x$). Figure 3d shows the impact on vertical heat flow with depth beneath the centre of the anomalous body. The model that approximates the one-dimensional problem predicts constant heat flow with depth, as expected. For the other models, the predicted reductions in vertical heat flow at depths close to the insulating body increase in proportion to $1/h_x$. The impact gradually reduces with increasing depth. This illustrates that the refraction of heat from vertical to lateral is concentrated close beneath the base of the insulating body, with the degree of refraction increasing as the width of the insulator decreases.

The key implications from the above modelling with respect to targeting geothermal resources in insulation-dominated geothermal systems can be summarised as follows.

(1) 1D heat-flow models are inadequate to predict the temperature beneath a buried insulating body of finite width.
(2) A reduction in surface heat flow relative to the underlying heat influx indicates the presence of a buried insulating body of finite width.

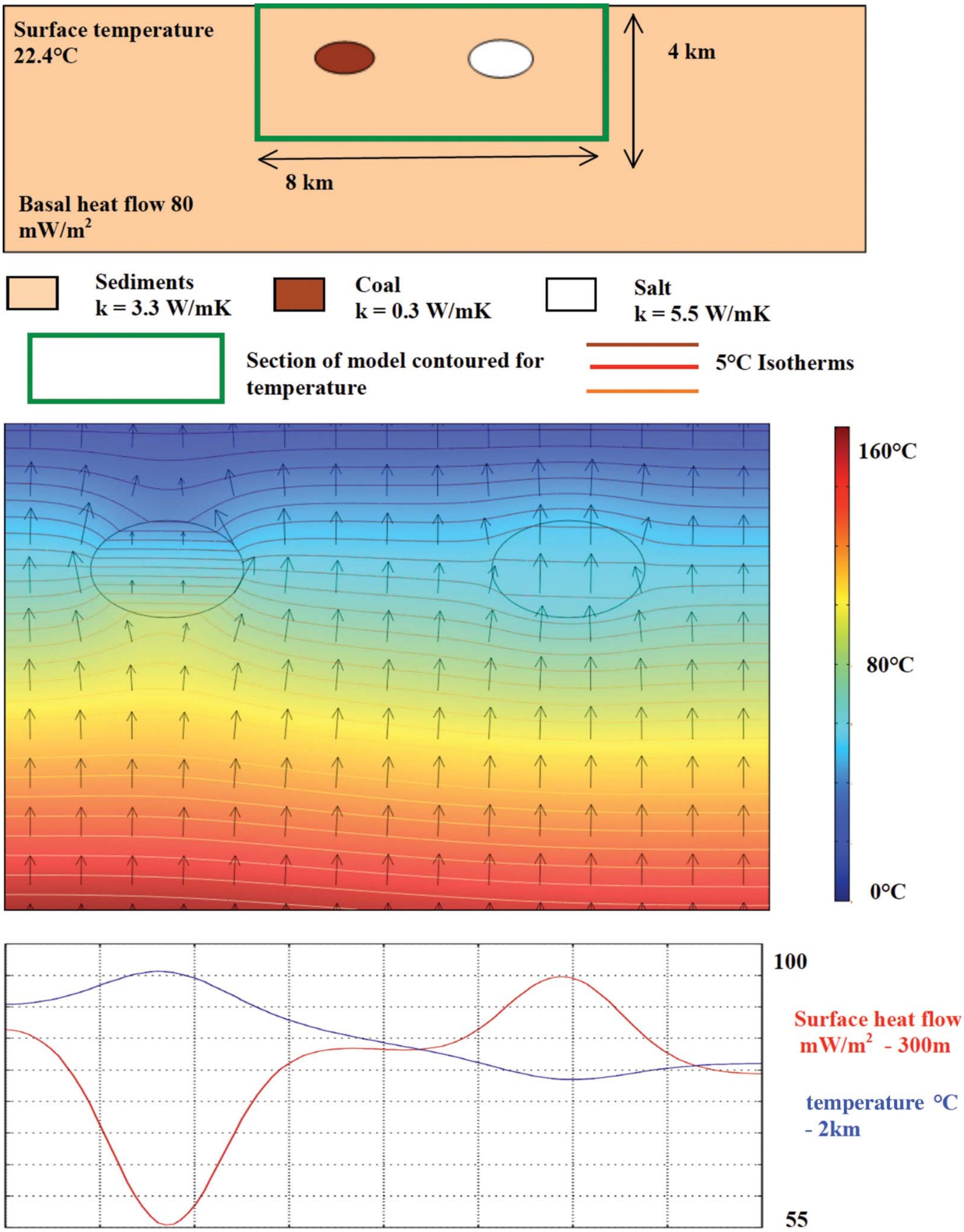

Figure 2 Effects of negative and positive conductivity anomalies on surface heat flow and temperature. In this example, the sediments have a thermal conductivity of 3.3 W/mK. A 1 km thick coal body (0.3 W/mK) centred at 1500 m depth results in depressed vertical heat flow at 300 m depth and increased temperature at 2 km depth. In contrast, a 1 km-thick salt body (5.5 W/mK) results in increased vertical heat flow at 300 m depth and decreased temperature at 2 km depth. After Wright (2008).

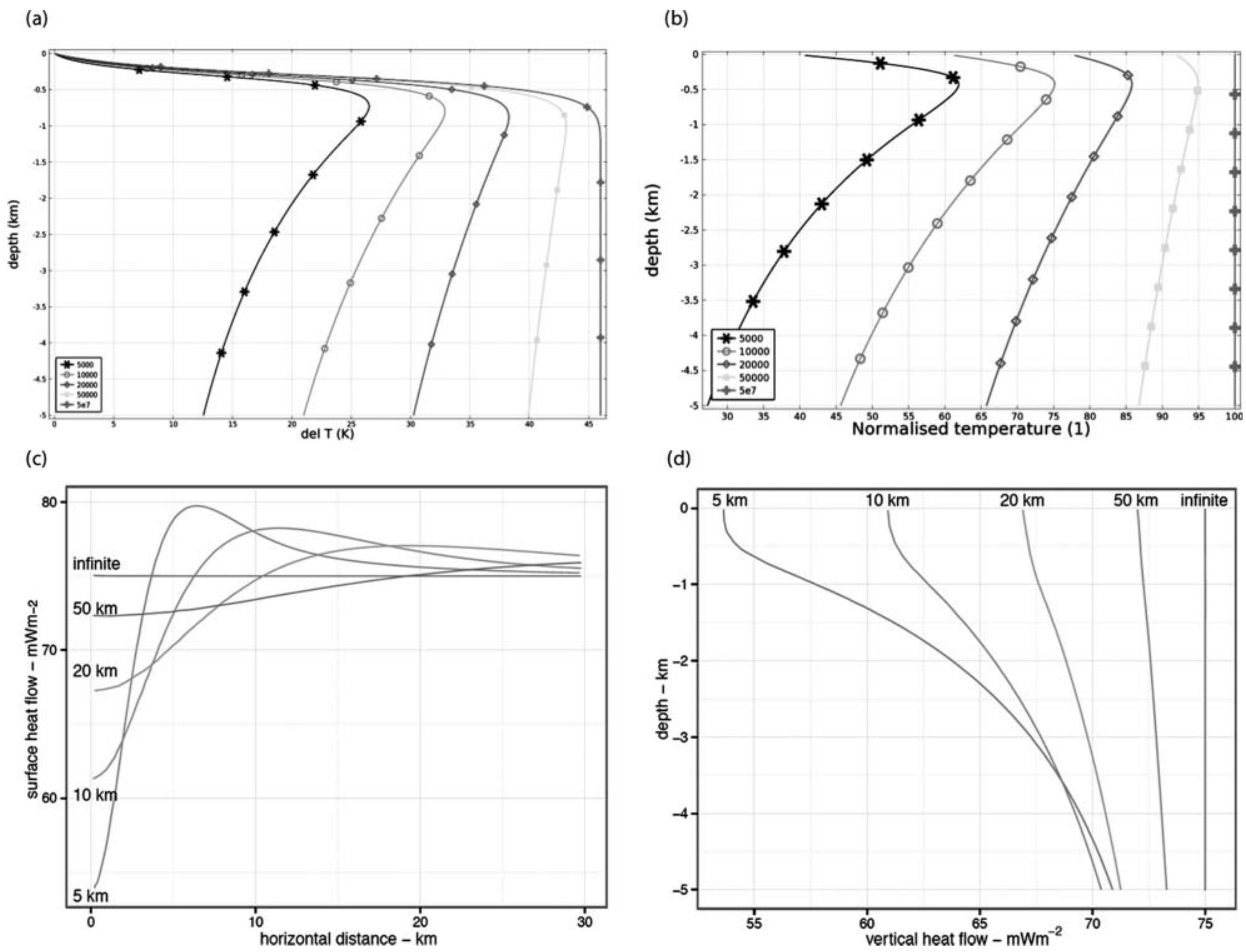

Figure 3 (a) Modelled temperature anomalies, as deviations from the reference state, with depth through the axis of symmetry of a buried insulator as defined in the text. Results are shown for five different characteristic widths of the insulator: 5 km, 10 km, 20 km, 50 km and 5000 km. The latter approximates the 1D solution. Note that the details of the calculated anomalies shown here are specifically for a smoothly varying conductivity source (as modelled), and that for a discrete confined source the near surface anomaly would be expected to be slightly negative. (b) As for (a), expressed as a percentage of the 5000 km case. (c) Predicted surface heat flow as a function of horizontal distance from the axis of symmetry for the models described in the text. Negative surface heat-flow excursions coincide with the axis of symmetry, while slightly positive anomalies occur at the edge of the insulating body. (d) Computed variations in vertical heat flow as a function of depth along the axis of symmetry for the models described in the text.

(3) The magnitude of the reduction in surface heat flow is a function of the width of the insulating body (and potentially the thickness of the body, although our modelling did not test this).
(4) A buried insulating body always results in elevated temperatures beneath the body relative to the reference case with no insulator.
(5) The 'insulation potential,' or degree of temperature elevation relative to the case with no insulator, increases with increasing width of the body.

In sedimentary basins with shallow buried insulators, therefore, highest temperatures are expected beneath areas with small, but observable, reductions in surface heat flow with respect to the underlying heat influx.

APPLICATION TO THE LATROBE VALLEY IN VICTORIA

The Latrobe Valley, in Victoria's Gippsland Basin (Figure 4), is potentially one of the best examples of an insulation-dominated geothermal target region in the world. It is estimated that the Latrobe Valley alone contains in excess of 53 000 million tonnes of 'economic' coal resource (Department of Primary Industries Victoria 2008). The wider Gippsland Basin contains as much as 200 000 million tonnes of coal (Department of Primary Industries Victoria 2008). Currently about 65 million tonnes of coal are extracted from the open cut mines within the Valley each year, accounting for 98.5% of Australia's brown coal extraction (Department of Primary Industries Victoria 2008).

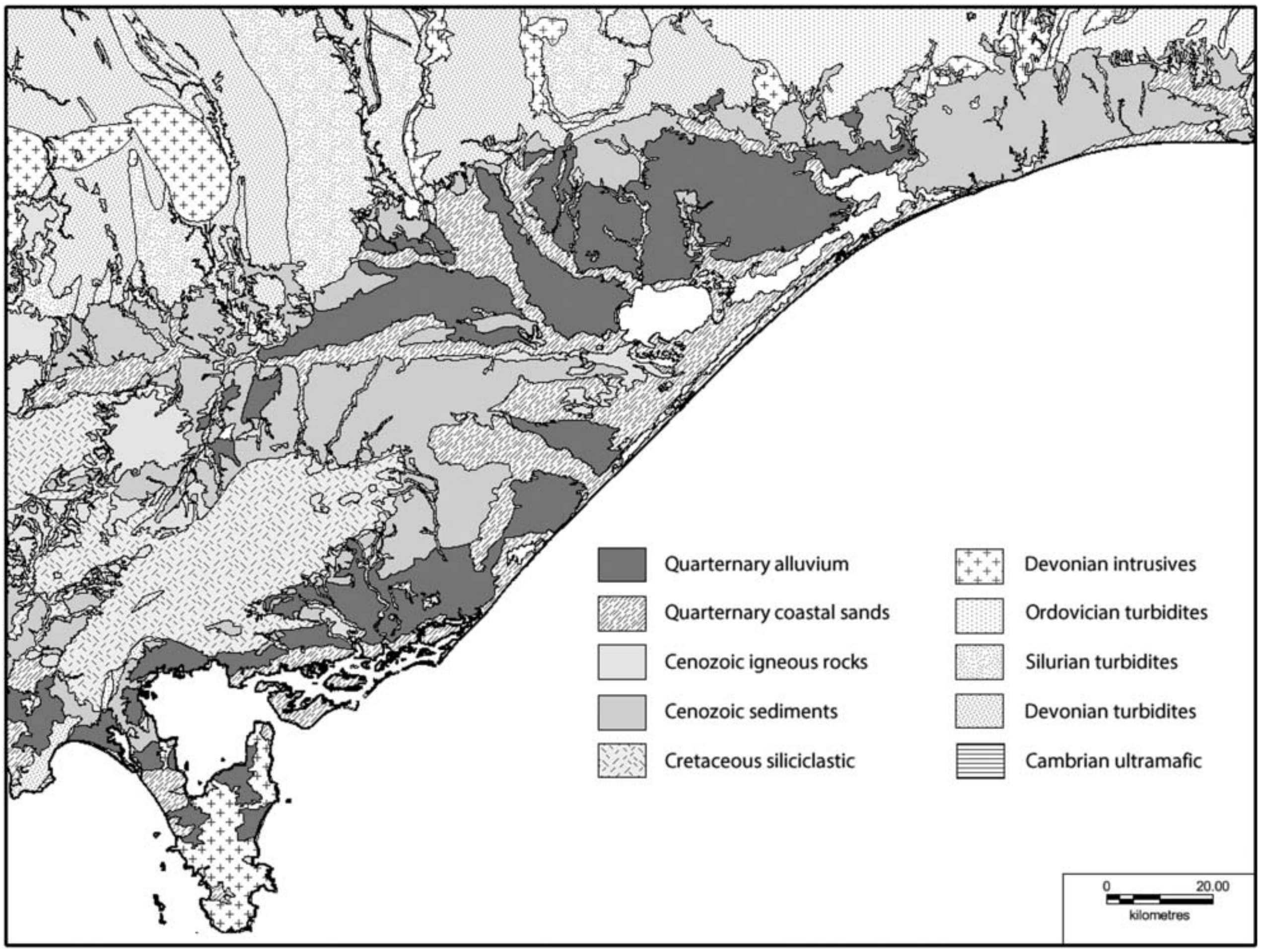

Figure 4 Geology of the onshore Gippsland Basin and Latrobe Valley region.

The Gippsland Basin is a large pericratonic rift basin that formed in a failed rift arm from the late Jurassic in response to rifting between Australia and Antarctica. The basin's present extent is on the order of 46 000 km^2, of which about two-thirds is offshore beneath present-day Bass Strait. The offshore portion of the basin contains significant petroleum resources including over 1 Tcf of natural gas and 4 billion barrels of oil accumulations. The resource systems of the onshore portion of the basin are dominated by thick brown coal sequences that provide fuel for the majority of Victoria's base load energy generation along with some largely unrealised unconventional gas resources.

The Latrobe Valley Depression formed on the western margin of the Gippsland Basin late in the rift cycle, which lasted from the Cretaceous to the Cenozoic (Figure 5). The basement to the Latrobe Valley Depression sequences comprises Paleozoic metasediments of the Melbourne Zone and overlying lower to middle Cretaceous rift-fill sandstones and claystones of the Strzelecki Group (Abele *et al.* 1998). The basement sequences were shortened during the middle Cretaceous to form the Southern Highlands, to the north of the Latrobe Valley. Subsequent late-stage rifting from the late Cretaceous to the Miocene, and associated slow but steady subsidence (sag-phase), resulted in the deposition of thick organic-rich swamp and brown coal (lignite) sequences (the Traralgon, Morwell and Yallourn formations) (Barton *et al.* 1993). These stacked coal sequences exceed 300 m thick in places within the Latrobe Valley (Holdgate *et al.* 1995).

Subsequent compression at the end of the Miocene inverted basin margin growth faults forming a series of SSW-trending monoclines, such as the Baragwanath Anticline, within the Traralgon, Morwell and Yallourn formations. Peneplanation of the swamp sequences followed in the Pleistocene, with the carbonaceous sediments buried by the thin gravels and sands of the Haunted Hills Formation (Abele *et al.* 1998).

The Traralgon Formation (Eocene to Oligocene) is the oldest coal-bearing sequence in the region and contains brown coal seams up to 80 m thick. These seams are interbedded with gravels, sands and clays throughout the formation. The overlying upper Oligocene to lower Miocene Morwell Formation consists of thick brown coal seams with interstitial gravel and sand layers. The Morwell Formation is on the order of 180 m thick where it is mined at the Morwell open cut, and increases to over 200 m in thickness to the east near Gormandale. The youngest coal-bearing sequence in the Valley is the middle to upper Miocene Yallourn Group. The deeper parts of this sequence are dominated by about 100 m of

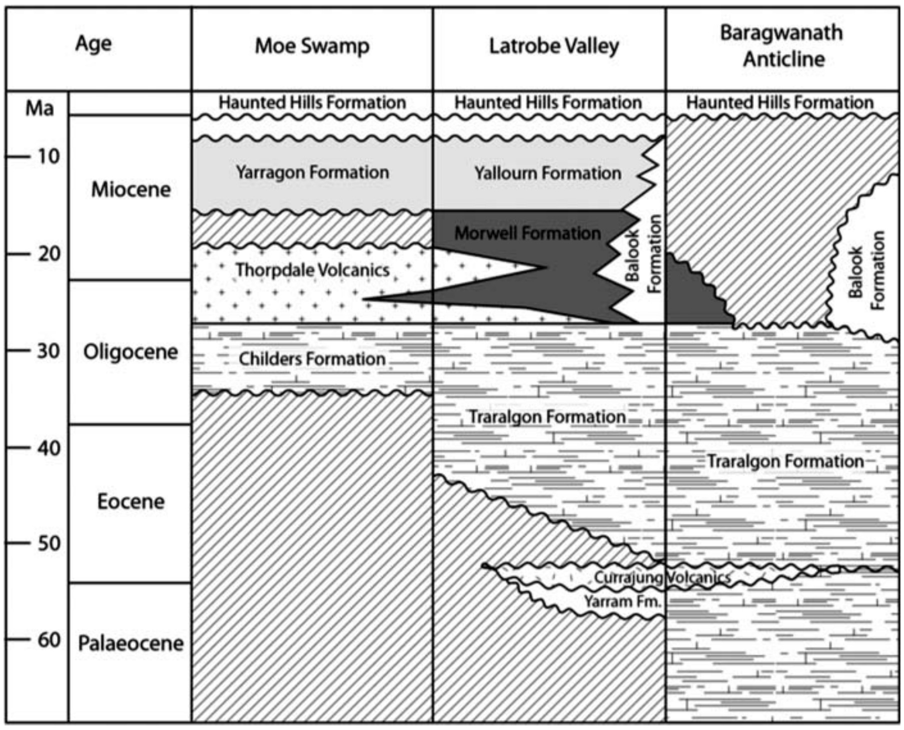

Figure 5 Stratigraphy of the Latrobe Valley Depression (after Abele *et al.* 1988; Jansen *et al.* 2003).

clay and sand with thin coals, but at shallower levels the coal dominates, and the main seam is almost 100 m thick (Holdgate *et al.* 1995).

In 2003, GeoScience Victoria and the Department of Primary Industries Victoria developed a series of 3D coal seam models over an area of about 2030 km^2 covering the Latrobe Valley (Figure 6a–c; Jansen *et al.* 2003), constrained by lithological records from 8445 bores. While many of these bores are shallow, less than 400 m, the majority do pierce all of the coal units and many intersect basement so constrain the geometry of the coal sequences well. In addition, a number of deeper tight gas exploration wells further constrain the geometry of the basement surface. The models captured the distribution and properties of coal seams down to a minimum seam thickness of 6 m. The models were attributed with properties including seam name, moisture content, silica content, ash content, net wet specific energy, etc.

In collaboration with the *AuScope Simulation, Analysis and Modelling Group* at Monash University, we ran a number of thermal forward models on a series of simplified versions of the 3D coal model (Figure 6d) in order to investigate the possible effect of the insulating coal cover on thermal refraction and the temperature structure at depth beneath the Latrobe Valley.

We carried out the thermal modelling using the *Underworld-GT* Lagrangian particle-in-cell finite-element code (Moresi *et al.* 2007; Quenette & Moresi 2010). *Underworld-GT* solves the non-linear heat-flow equation in a 3D parallel environment, providing one of the few robust tools that can simulate, or forward model, heat flow and heat refraction effects at the basin scale (hundreds to thousands of square kilometres of areal extent) but still maintain the vertical resolution to include thin coal layers within the starting model.

Two 3D models were developed in order to test the effects of insulating coal measures on the thermal structure of the Latrobe Valley. The first was an idealised model in which a simple 500 m-thick coal filled half-graben (thermal conductivity of 0.3 W/mK) was buried to a depth of 1 km and contained within a homogeneous host sequence (thermal conductivity of 2.2 W/mK). A forward model was run for this geometry and is presented in Figure 7. This model in a sense is a three-dimensional (3D) extension of the simple 2D model presented in Figure 2 but shows in more detail the effect on the temperature distribution owing to insulation and heat refraction within the volume as well as the surface heat flow above the insulating body.

The second model that was forward modelled for heat flow and temperature using *Underworld-GT* was based on a significantly more detailed and realistic representation of the Latrobe Valley geology and coal sequence geometries. Owing to the very high resolution of the starting model (Figure 6a–c), the geology of the Latrobe Valley was consolidated into just five units based on 3D geostatistical down-sampling using Gocad. Each of the resulting units was then assigned a uniform thermal conductivity based on published datasets for the region (Beardsmore & Cull 2001; Wright 2008; Harrison *et al.* 2012) and measurements made in the petrophysics laboratory at the University of Melbourne. The conductivities used in the simulation were:

(1) basement—2.25 W/mK;
(2) transition zone marginal coal units—0.65 W/mK;
(3) major coal seams—0.5 W/mK;

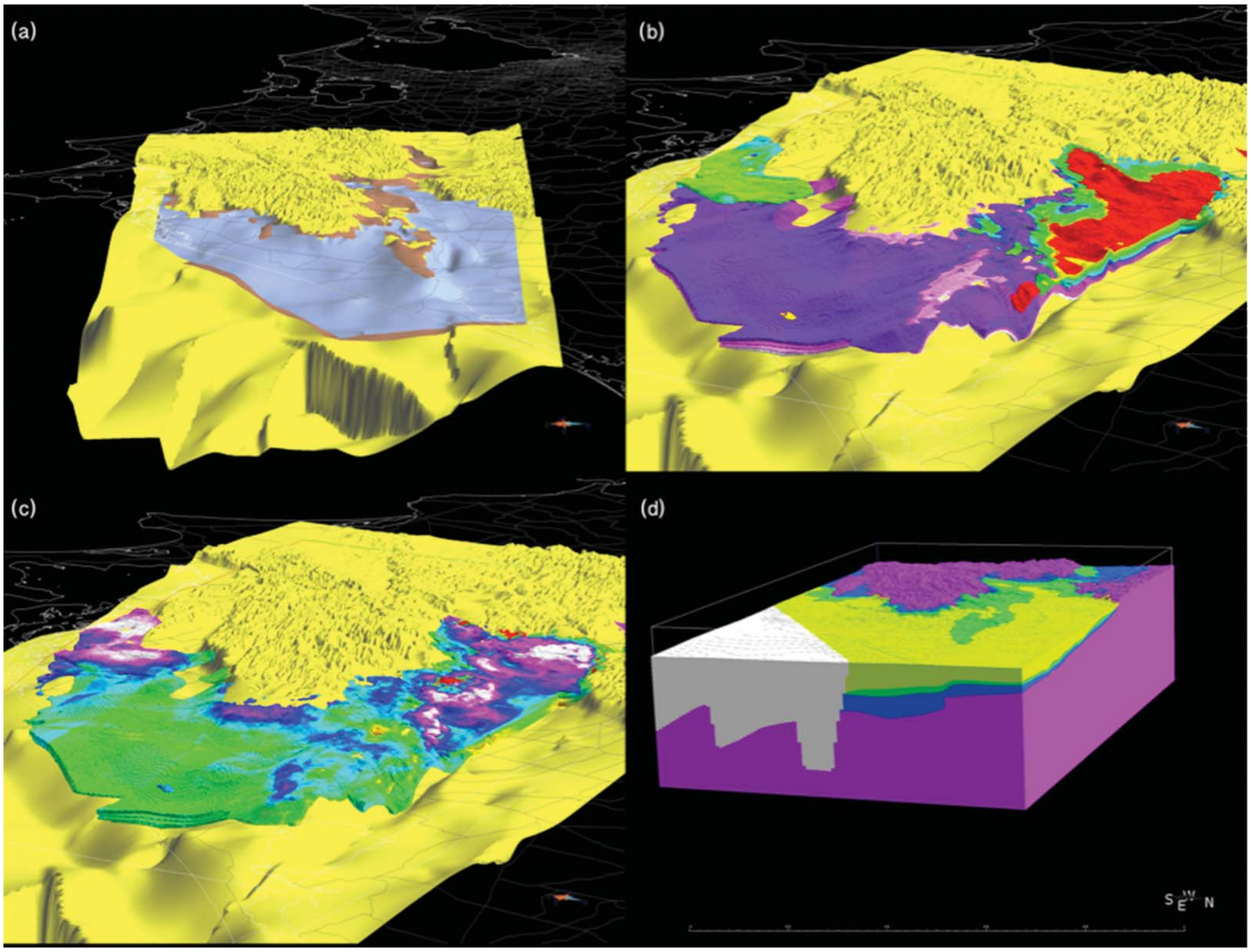

Figure 6 3D models of coal seam distribution and generalised thicknesses in the Latrobe Valley region of the Gippsland Basin. (a) Perspective view of the model volume from east to west. Yellow represents the top of the economic basement. (b) Distribution of coal seams coloured by seam name. (c) Coal seams coloured by moisture content. (d) Voxelised simplified geological model of the Latrobe Valley; purple, basement; blue, transition zone marginal coal units; green, major coal seams; lime, Haunted Hills Gravel; white, offshore graben sequences.

(4) Haunted Hills Formation—2.6 W/mK;
(5) offshore graben sequences—2.4 W/mK.

We applied a uniform heat flow of 87 mW/m^2 to the base of the model and assumed no internal radiogenic heat production. The basal heat flow is consistent with a recent heat-flow determination in the Tynong-1 borehole to the northwest of the Latrobe Valley (Harrison *et al.* 2012) where we expect no thermal effect from buried insulation. The authors acknowledge that an assumption of uniform basal heat flow across the model is likely an oversimplification, and that the actual basal heat flow is likely to vary over the Latrobe Valley and surrounding region because of variations in mantle heat input and heat generation within the crust.

Models of this type are valuable as visualisation tools (Figure 8) but should not be interpreted as accurate predictions of the actual 3D temperature field. Instead, the particular outcomes from this model illustrate the general effect of buried coal seams of pseudo-realistic thickness and distribution beneath the Latrobe Valley. The isotherms predicted by the model (Figure 8f) clearly show the influence of the thermal insulation layers. The 150°C isotherm surface (Figure 8e), for example, has an inverted geometry that mimics the coal thickness above. That is, locations where the 150°C isotherm is closest to the surface correspond to the thickest sections of insulating coal. The shallow 25°C isotherm (Figure 8g), on the other hand, mimics the geometry of the topography (or the top of the model volume).

Both the 1D and 2D heat-flow modelling presented earlier in this paper predict that negative surface heat-flow anomalies can be indicative of buried insulators (and as such potential for trapped high temperatures beneath). The 3D modelling of the realistic coal geometries for the Latrobe Valley support this observation with a subtle but measurable negative heat-flow anomaly in the region above the thick coal sequences (Figure 8i). As with the 1D examples, an edge effect can also be identified where a narrow band of elevated surface heat flow coincides with the edge of the insulating coals. The depressive effect on shallow surface temperatures immediately above the coals is not as pronounced in the realistic example as in the simple half graben in

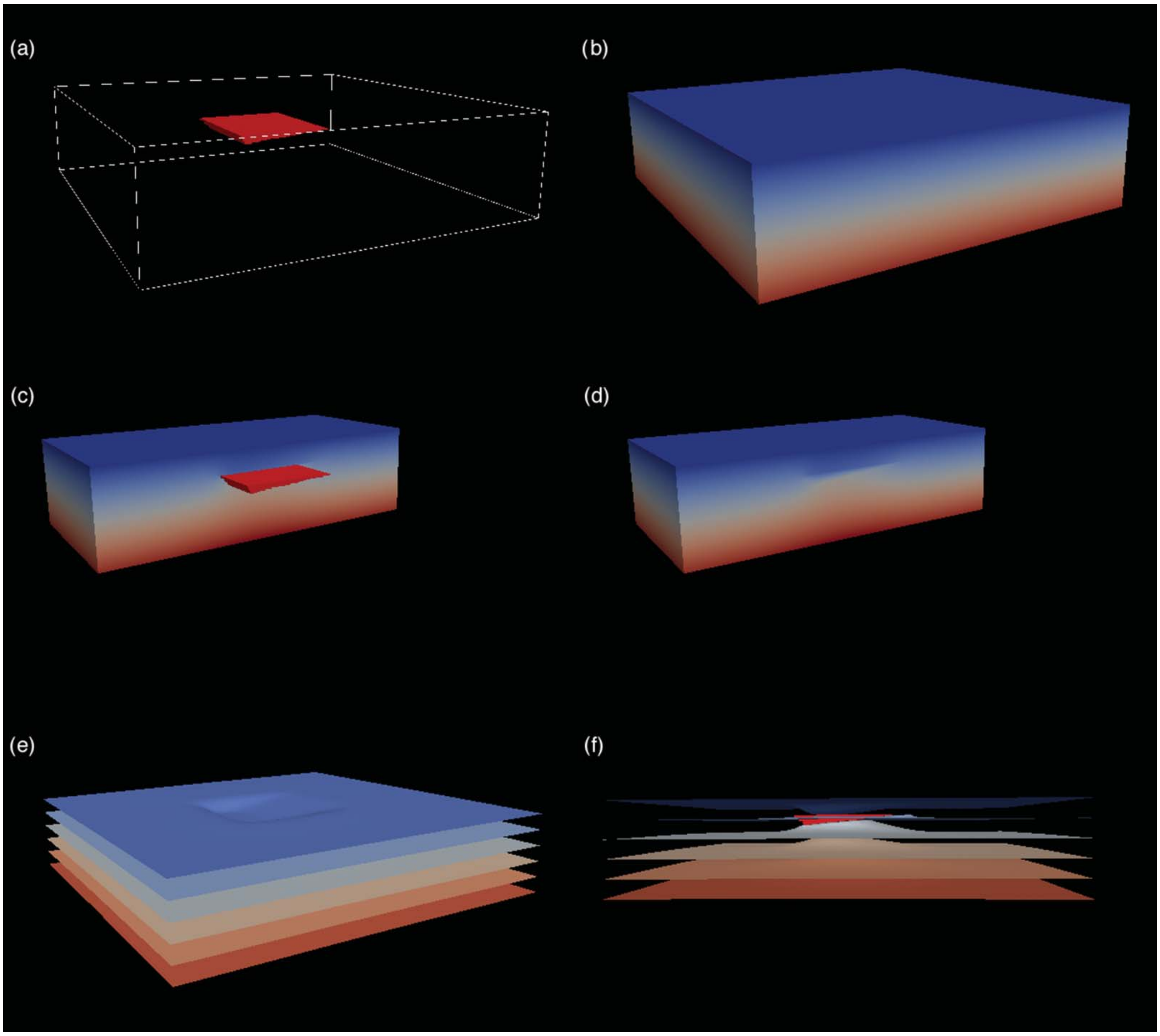

Figure 7 *Underworld-GT* model for an 'idealised' coal filled half graben. (a) Starting model for coal filled half graben (thermal conductivity 0.3W/ mK) in a homogeneous host (thermal conductivity 2.2 W/mK); (b) temperature field; (c) cutaway of temperature field showing heat trapping beneath low conductivity half graben; (d) cutaway of temperature field through graben showing both heat trapping and negative surface heat-flow anomaly above insulator; (e) and (f) temperature isotherms. Isotherms are 50°C increments from 25°C to 275°C.

Figure 7, owing in part to the fact that in reality, the coals are partially eroded, whereas in the simplified example, the coals are completely buried within the higher conductivity material.

Comparison between the coal-dominated model and a 'base' condition model that contains no coal but the same boundary conditions indicated that the Latrobe Valley coal measures elevate the temperature of the rocks at 4 km depth by between 30 and 35°C. This effectively increases the average geothermal gradient to this depth by about 30%. These results are comparable with those attained in a similar 3D heat-flow modelling study of the Sydney Basin by Danis *et al.* (2012) where the forward modelling was also carried out using the *Underworld-GT* simulation package.

In its prospectus, Greenearth Energy (2007) published a surface heat-flow map of parts of the onshore Gippsland Basin (Figure 9), including the Latrobe Valley. One of the authors of this paper directed the production of the map for Greenearth Energy and is aware of the broad uncertainties associated with many of the specific surface heat-flow values underpinning the map. The uncertainties related to a range of assumptions around the thermal conductivity of specific rock units and the quality of temperature data from the boreholes.

In general, the patterns of heat flow observed on Figure 9 are consistent with the modelling in this paper. Pronounced regions of low surface heat flow are flanked by regions of slightly elevated surface heat flow, relative to the global average of about 64 mW/m^2 for Mesozoic aged basins (Beardsmore & Cull 2001). The patterns point to heat-refraction effects in the basin. To examine whether the distribution of insulating coal in the basin can explain the magnitude and distribution of the

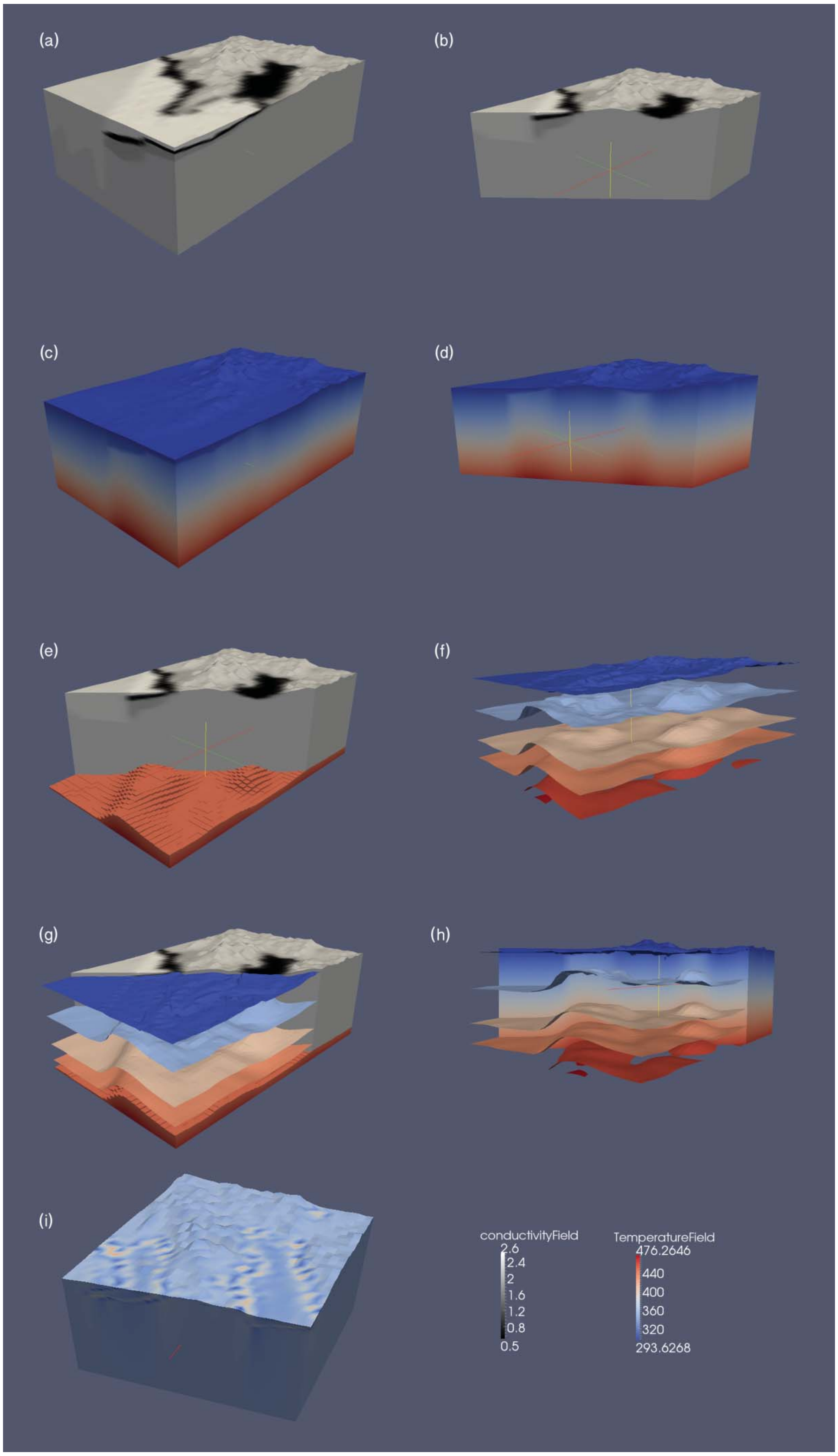

Figure 8 *Underworld-GT* results for the model in Figure 6d. (a) Perspective view of the model looking to the SW, coloured according to thermal conductivity (see legend for scale in W/mK). (b) As for (a) but cut away perpendicular to the Latrobe Valley Depression. (c) and (d) Predicted temperature fields for the model volumes shown in (a) and (b), respectively (see legend for scale in kelvin). (e) Predicted 150°C isotherm. (f) Predicted 20°C, 50°C, 100°C, 125°C and 150°C isotherms. (g) Predicted isotherms with conductivity volume. (h) Predicted isotherms with temperature volume. (i) Vertical heat-flow field, $q = -k(dT/dz)$, highlighting the weakly depressed heat-flow values (blue) above the coal sequences and the enhanced heat-flow values (white-red) at the margins of the coals.

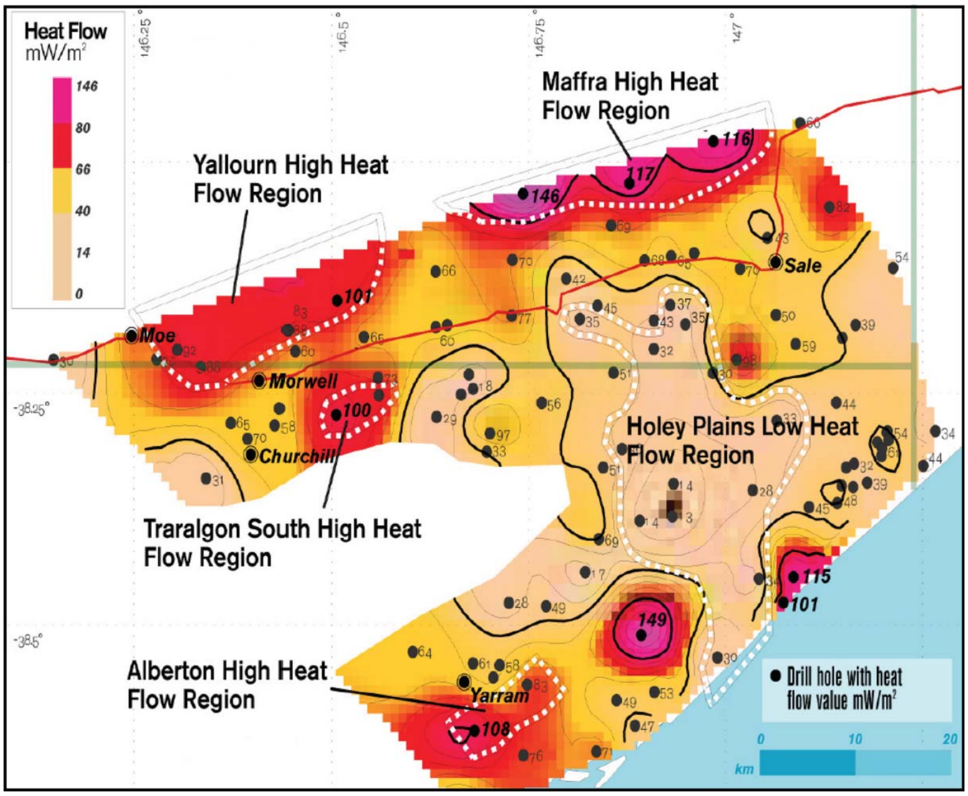

Figure 9 Heat-flow map for parts of the onshore Gippsland Basin (Greenearth Energy 2007).

surface heat-flow pattern in Figure 9, we were able to make use of an existing detailed 3D geological model of the coal seams in the Latrobe Valley.

Again, the 3D forward models presented here contain many simplifications and assumptions that make them unreliable for an economic assessment of geothermal potential. They are not constrained by real heat flow or accurate thermal property data. Potential complicating factors such as heterogeneous basal heat flow or lateral heat redistribution via groundwater flow are entirely ignored. Each of these could have a significant impact on actual temperatures at depth and the geothermal potential beneath the Latrobe Valley. However, all other factors being equal, this modelling does clearly illustrate that the most prospective target regions for elevated temperature are those beneath thick insulating cover (thick brown coals in the context of the Latrobe Valley). Given the very low thermal conductivity of coal, even modest coal accumulations can significantly improve the economic viability of geothermal energy within a basin.

CONCLUSIONS

Thick coal sequences can elevate the temperature of the rock beneath them enough to significantly improve the economic viability of geothermal energy extraction. The modelling presented in this paper demonstrates some tools and targeting strategies for geothermal explorers dealing with insulated systems (for example, targeting negative surface heat-flow anomalies above thick coal sequences). However, the beneficial thermal effect of thick coal units is somewhat offset by other characteristics of coal that affect the ease with which potential geothermal reservoir units can be identified using traditional geophysical methods.

Not only do thick coal sequences act as very effective thermal insulators, but they also absorb large amounts of seismic energy. As a result, the most precise and accurate geophysical tool for characterising basin geometries and petrophysical properties, reflection seismic surveying, often generates very poor data in the presence of coal. The seismic signals are strongly attenuated and as a result it is very difficult to effectively image potential reservoirs beneath the coals, or even to define the shape of the confining basin.

Given that geothermal explorers are equally concerned about finding permeable rocks (or rocks in which permeability can be enhanced) as they are with locating elevated temperatures, this is a particular problem. In the absence of effective seismic reflection data, new geophysical techniques need to be developed to characterise permeability at depth beneath coal-rich sequences like the Latrobe Valley without resorting to prohibitively expensive drilling programs.

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APPENDIX. FINITE-ELEMENT SIMULATION OF A BURIED CONFINED INSULATOR

We used the finite-element package COMSOL (v4.0) to model the impact of a buried, confined insulator as described in this paper. We modelled a half-space of a symmetrical insulating thermal conductivity anomaly according to Equation 3. The modelled domain was 15 km deep and 50 km wide. We use a variably sized triangular mesh with a minimum spacing of ~15 m in the region of maximum interest (at $x = 0$, $z = 0$), increasing to 3.3 km at the maximum reach of the model ($x = 50$ km, $z = -15$ km). A uniform heat-flow condition of $q = 75$ mW/m^2 was applied to the base of the model, while lateral boundaries were defined as perfect insulators (zero heat loss through the side boundaries). The surface was assigned a constant temperature of 0°C.