

Unlocking Geothermal Potential in the Onshore Gippsland Basin Using a 3D Geological and Thermal Modelling Approach

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ABSTRACT

Exploring geothermal energy in sedimentary basins is challenging due to complex geology, limited deep thermal data, and a historical focus on hydrocarbons. This study addresses this by integrating 3D geological modelling and heat flow simulation of a section of the onshore Gippsland Basin in southeastern Australia to better understand its thermal structure and identify suitable areas for geothermal development. Using Leapfrog Energy, we built a high-resolution (100 m) 3D geological model integrating topography and prior horizons interpreted from boreholes/wells, seismic, and gravity data. The model covers key stratigraphic units, including the Haunted Hills Formation, Tertiary coal units, Cenozoic sediments, and deeper basement rocks. Special attention was given to a Cenozoic sedimentary unit hosting a regional aquifer with potential for geothermal energy in the 30–70°C range. We mapped this unit's spatial extent beneath a 61 × 73 km study region to estimate its groundwater storage capacity and heat-in-place. To explore heat movement, the upper 2.6 km of the model was imported into Underworld3, a thermal simulation tool. By assigning realistic rock properties and applying preliminary boundary temperature conditions, a steady-state temperature model of the subsurface was produced. The results revealed zones of elevated temperature, structurally focused heat flow, and areas where target temperatures can be reached at economical drilling depths. This workflow offers a powerful method for assessing geothermal resources using existing geological data and open-source modelling software, providing a foundation for further refinement, resource evaluation, well targeting, and the development of a geothermal energy industry in the Gippsland Basin.

1 INTRODUCTION

The onshore Gippsland Basin in southeastern Australia hosts substantial geothermal potential but remains largely underexplored compared to its well-documented coal, petroleum, and groundwater resources. Despite extensive geological and hydrocarbon studies, a comprehensive understanding of the thermal regime is still lacking. Previous investigations highlight a significant gap between available temperature data and the requirements for robust geothermal resource assessment. Bridging this gap demands an integrated approach that combines geological, hydrogeological, and thermal modelling methods. This study aimed to develop an end-to-end workflow to compile and quality-control temperature and lithological data from coal, groundwater, and petroleum boreholes; construct a geologically constrained 3D framework model; and perform steady-state heat-flow simulations incorporating realistic boundary conditions.

The initial focus was on the development of a high-resolution static model as the foundation for subsequent thermal simulations. The model defined the basin's stratigraphic architecture based on key horizons, with particular emphasis on a Cenozoic sedimentary unit that hosts an aquifer identified as a principal regional source of geothermal energy in the 30–70 °C range. The Cenozoic sedimentary unit overlies a non-marine Lower Cretaceous sedimentary unit called the Strzelecki Group and is capped by thermally insulating Cenozoic coal deposits. These coal layers restrict upward heat conduction, elevating underlying temperatures, and creating conditions favorable for geothermal exploitation. The static model provided the framework for a preliminary characterization of the basin's thermal structure through integrated geological and numerical temperature modelling.

1.1 Location of study area

The study area lies approximately 250 km east of Melbourne in southeastern Australia (Figure 1), within the onshore Gippsland Basin. The Gippsland Basin covers an area of about 56,000 km², of which the onshore portion comprises roughly 16,000 km² (Holdgate and Gallagher, 2003) bounded to the south by the coastal margin and to the north by the uplifted Paleozoic basement of the Eastern Highlands (Figure 1). The basin is one of Australia's most resource-rich geological provinces, hosting extensive oil, gas, and brown coal deposits, as well as

significant groundwater systems. One of these groundwater reservoirs represents an emerging target for geothermal energy development (Beardsmore, 2024).

The study area encompasses a 61 x 73 km region covering the Latrobe Valley, which hosts major brown coal deposits. This setting provides a unique opportunity to investigate heat storage and transfer processes within thick sedimentary sequences influenced by coal insulation and structural heterogeneity.

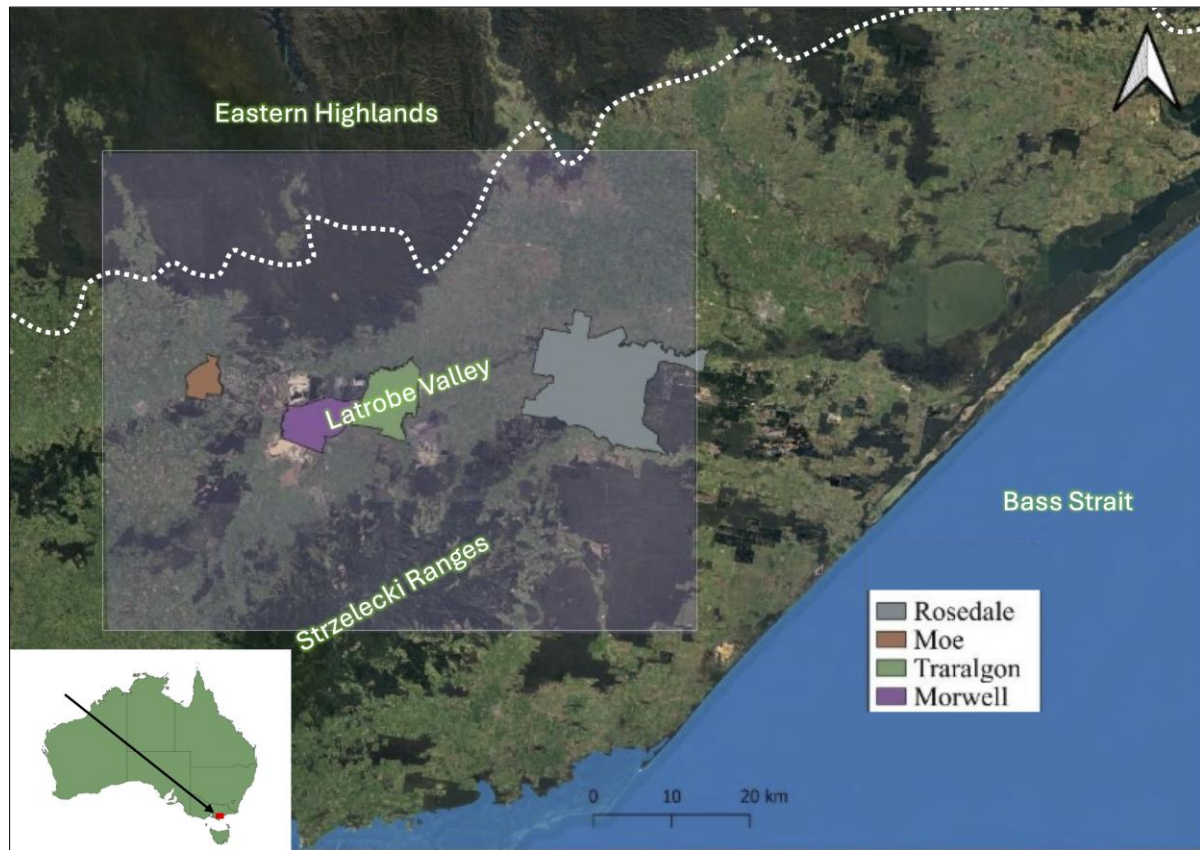


Figure 1. Location of study area (shaded box) in SE Australia, showing the approximate northern extent of the onshore Gippsland Basin (white dashed line), major geographic features, and major population centers.

1.2 Stratigraphy

The stratigraphic succession of the onshore Gippsland Basin records a long and complex sedimentary history from the Paleozoic to the Pliocene (Figure 2). From oldest to youngest, the major stratigraphic units include Paleozoic metasedimentary and granitic basement rocks, the non-marine (largely fluvial) Strzelecki Group, Cenozoic siliciclastic sediments, Cenozoic coal-bearing formations (Latrobe Valley Deposit, LVD), and Late Pliocene alluvial and coastal deposits (Holdgate and Gallagher, 2003; Mahon and Wallace, 2020).

The principal geothermal target in this study is the Cenozoic aged transitional siliciclastic/lower parts of Traralgon Formation (Fu et al., 2023). This formation consists predominantly of thick, fine- to coarse-grained siliciclastic sequences that overlie the Strzelecki Group (Figure 2). This formation acts as a significant regional aquifer, while the overlying Cenozoic coal sequences of Traralgon, Morwell, Yallourn and Hazelwood Formations provide thermal insulation that helps retain heat within the deeper sedimentary layers. Together, these lithological relationships create favorable conditions for hot sedimentary aquifer development within the onshore Gippsland Basin.

Epoch Series	International planktonic foraminiferal zones	Onshore Gippsland Basin Stratigraphy			
		Australian Stages & spore–pollen zones		LVD	Rosedale
PLIOCENE	LATE	N20-23	T. pleisto	Haunted Hill Formation	Haunted Hill Formation
	EARLY		M. lipsis		Boisdale Formation
		N18-19	Kalimnan		
MIOCENE	LATE	N16-17	Mitchellian	Hazelwood Formation	Lake Wellington Formation
	MIDDLE	N10-15	Bairnsdalian		
		N8-9	Batesfordian/Balcombian	Yallourn Fm	
		N7			
	EARLY	N6	Longfordian		
		N5			
OLIGOCENE		N4			
	LATE	P18-22	Janjukian		
	EARLY				
EOCENE	LATE	P15-17			
	MIDDLE	P10-14			
	EARLY	P6-9			
PALEOCENE	LATE	P5			
	MIDDLE	P2-4			
	EARLY	P1			
PRE-TERTIARY				Strzelecki Group / Paleozoic	

Figure 2. Stratigraphy of the Latrobe Valley Deposit (LVD) underlying Traralgon and Morwell, and beneath Rosedale further east. Modified from Holdgate and Gallagher (2003).

1.3 Structural setting

The tectonic history of the onshore Gippsland Basin reflects multiple phases of deformation and basin development. The region experienced three main periods of structural development: extension and faulting associated with early Cretaceous rifting (Power et al., 2001); Mid to Late Cretaceous extension linked to the breakup of eastern Gondwana; and Oligocene compression that produced widespread folding and reactivated reverse faults across the basin (Mahon and Wallace, 2020).

These tectonic phases collectively influenced the basin's present-day architecture, shaping the distribution of sedimentary formations, controlling fault orientations, and establishing thermal conductivity contrasts that control the conductive flow of heat through the onshore Gippsland Basin. Figure 3 shows the major structural elements.

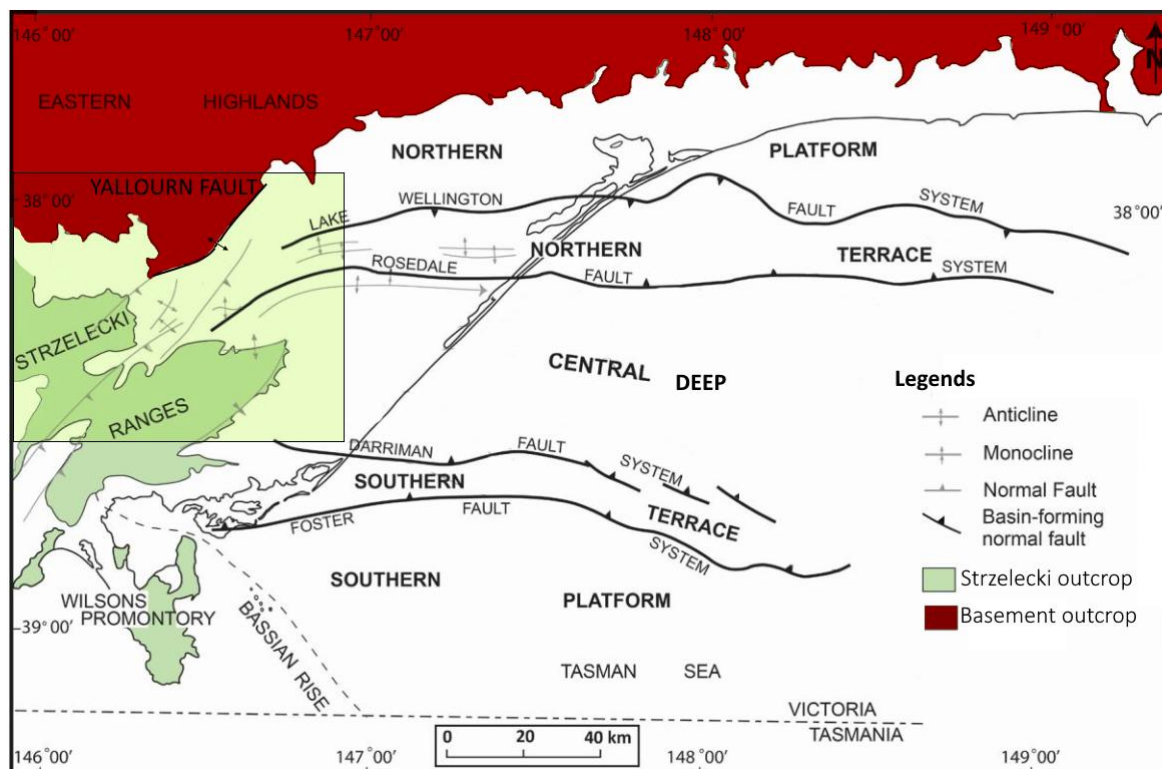


Figure 3. Major faults and structures of the onshore and near-offshore Gippsland Basin, along with Strzelecki Group and Paleozoic basement outcrops. Modified from Mahon and Wallace (2020). Rectangular shape on the map shows approximate extent of the study area.

1.4 Previous work

The onshore Gippsland Basin has been extensively studied for its hydrocarbon and coal resources; however, its geothermal energy potential remains comparatively underexplored. Previous studies such as Leonard and King (1992) and Beardsmore (2024) have highlighted that the regional aquifer hosted within Cenozoic siliciclastic sediments has potential to support geothermal energy initiatives that utilize water temperatures ranging from 30 to 70 °C. Other previous studies have reported terrestrial heat flow values ranging between 35 and 105 mW/m² and average geothermal gradients of 35–80 °C/km within groundwater bores. Localized geothermal gradients can exceed 130 °C/km in bores intersecting thick layers of Cenozoic brown coal (Harrison et al., 2012; O’neill et al., 2022). (Harrison et al., 2012) Most prior research, however, has been limited to one-dimensional thermal analyses of individual bores and has not utilized 3D numerical modeling to elucidate the thermal structure of the basin. The exception is Rawling et al. (2013), who examined the possible influence of thermal conductivity on temperature distribution with a focus on the onshore Gippsland Basin.

2 METHODOLOGY

2.1 Geological model

A 3D geological model of a portion of the onshore Gippsland Basin was constructed using Leapfrog Energy to integrate topography with geological horizons previously interpreted by other researchers from borehole, seismic, and gravity data. Key stratigraphic surfaces were adopted from previous models by GHD (2011) and Powell et al. (2020), and were recombined based on the aim of this study.

The Leapfrog model covered an area of approximately 61 × 73 km as shown on Figure 1 and extended to a depth of 10 km, encompassing key stratigraphic units from the surficial Haunted Hills Formation to the Paleozoic basement. A uniform horizontal grid resolution of 100 m was applied to maintain sufficiently detailed representation of geological boundaries for subsequent geothermal resource assessment.

The upper surface of the static model was defined as the present topography. Four principal horizons were defined to represent the stratigraphy: (1) the top of the Yallourn Formation, representing the uppermost Cenozoic coal-bearing unit; (2) the top of the Cenozoic siliciclastic sediments, the primary geothermal target rock; (3) the top of the Strzelecki Group, and; (4) the top of the Palaeozoic basement. These surfaces were

extracted and regridded from previously published regional datasets and extrapolated to the edges of the new model where data were sparse at depth. Figure 4 shows one visualization of the Leapfrog model.

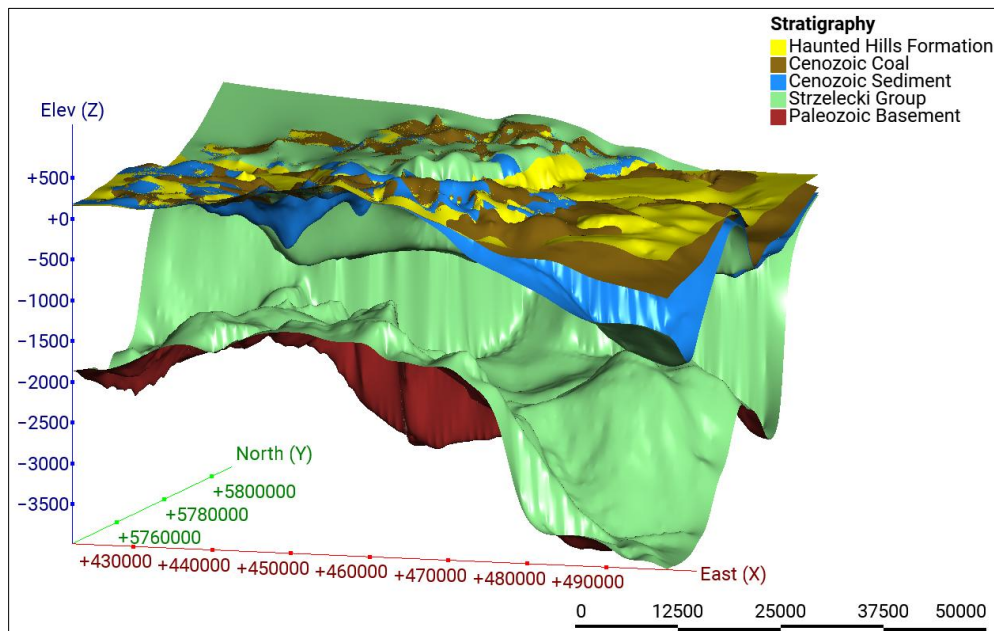


Figure 4. A visualization of the principal stratigraphic horizons of the 3D geological static model. Top of the Cenozoic Coal adopted from Powell et al. (2020); Top of Cenozoic Sediments created by integrating 2D surfaces from Powell et al. (2020) and O’neill et al. (2022); Top of Strzelecki Group and Top of Paleozoic Basement rocks from Powell et al. (2020).

2.2 Thermal properties and numerical simulations

Thermal modelling was conducted using the open source Underworld3 geodynamic simulator, which employs a finite-element framework to solve heat transfer equations in three dimensions (Moresi et al., 2025). Underworld3 allows flexible mesh generation, efficient parallel computation, and integration of geological models exported from Leapfrog Energy. The thermal model was used to investigate how the lithological and structural complexity influences the steady-state temperature distribution and heat flow pattern across the study region.

The Underworld3 model domain measured approximately $61 \times 73 \times 2.6$ km, corresponding to the lateral extent of the Leapfrog Energy static model cropped to the top 2.6 km. A uniform cell size of 100 m was selected on all three axes (~11.7 million cells) to balance computational efficiency with spatial resolution, and to ensure consistency with the resolution of the static geological framework. The simulation assumed conductive heat transfer, which is the dominant heat transfer mode within the crust. No evidence has yet been found for convective heat transfer in the Gippsland basin.

Underworld3 implements Poisson’s equation for steady state heat conduction:

$$\nabla \cdot (k \nabla T) + A = 0$$

where k is thermal conductivity (W/m.K) and A is volumetric heat generation rate (W/m³). The thermal model, therefore, required the definition of thermal conductivity and volumetric heat generation rate for each of the defined stratigraphic units. Thermal conductivity was calculated as the average of laboratory measurements reported by Antriasian et al. (2015) for each of the units. Volumetric heat generation rate was assumed to be due entirely to radioactive decay of uranium, thorium, and potassium isotopes within the units (Beardsmore and Cull, 2001; Liu and Nasr, 2019). Elemental abundance data were not available so a proxy empirical relationship between heat generation and gamma-ray log data was used, as published by Rybach (1986):

$$A = 0.0145 \times (GR - 5.0)$$

where A is the volumetric heat generation rate ($\mu\text{W}/\text{m}^3$), and GR is the gamma-ray log reading in American Petroleum Institute (API) units. Gamma ray log data were examined for several petroleum wells on the onshore Gippsland Basin. GR log values in the Strzelecki Group interval, for example, were on the order of ~200 API,

corresponding to a volumetric heat generation rate of $\sim 2.8 \mu\text{W}/\text{m}^3$. Table 1 presents the estimated values of k and A for each modelled stratigraphic unit.

Table 1. Average thermal conductivity of modelled stratigraphic units calculated from data reported by Antriasian et al. (2015); estimated volumetric heat generation for each unit.

Stratigraphic unit	k (W/m.K)	A ($\mu\text{W}/\text{m}^3$)
Haunted Hills Formation	2.3	0.0
Cenozoic Coal	0.5	0.22
Cenozoic Sediment	2.0	1.38
Strzelecki Group	2.1	2.83
Paleozoic Basement	3.5	1.09

A preliminary thermal model was constrained using boundary thermal conditions estimated from regional datasets and borehole temperature measurements. Dirichlet boundary conditions were applied at the upper and lower surfaces, fixing temperature values and ensuring thermal stability during model convergence. Lateral boundaries were treated as adiabatic (no heat flux) to prevent artificial heat inflow or outflow through the model sides, thereby minimizing edge effects (Lemenager et al., 2018).

A mean land surface temperature (LST) of 15°C was applied as the top boundary, estimated from a national map of mean LST for mainland Australia at $1 \text{ km} \times 1 \text{ km}$ resolution published by Haynes et al. (2018). The bottom boundary temperature was set at a uniform 100°C at 2.6 km below sea level. While the actual temperature at 2.6 km is assumed to vary across the model area, the adopted constant value allowed an investigation of the likely impact on temperature distribution due to uneven volumetric heat generation and thermal refraction due to the significant thermal conductivity contrasts. 100°C at 2.6 km depth is approximately consistent with average bottom-hole temperature (BHT) data from petroleum and groundwater wells across the onshore Gippsland Basin.

Visualization and post-processing of the calculated steady temperature and heat flow distribution in the model was achieved using the pvmesh module within Underworld3 and with open source Paraview code.

3 RESULTS AND DISCUSSION

3.1 Temperature distribution within the model space

The steady-state thermal simulation revealed a distinct vertical and lateral variation in subsurface temperature (Figure 5). Although the modeled temperature field was constrained to a constant 15°C at the surface and a constant 100°C at 2.6 km depth, significant variation in temperature distribution is evident in the interior of the model. Elevated temperatures occur at shallower depths beneath the thickest coal-bearing formations in the center of the model, while lower temperatures occur towards the edges where coal is thinner or absent (Figure 6). These observations emphasize the impact of lithologic and structural controls on heat distribution within the coal-bearing basin and are consistent with the previous findings of (Rawling et al., 2013).

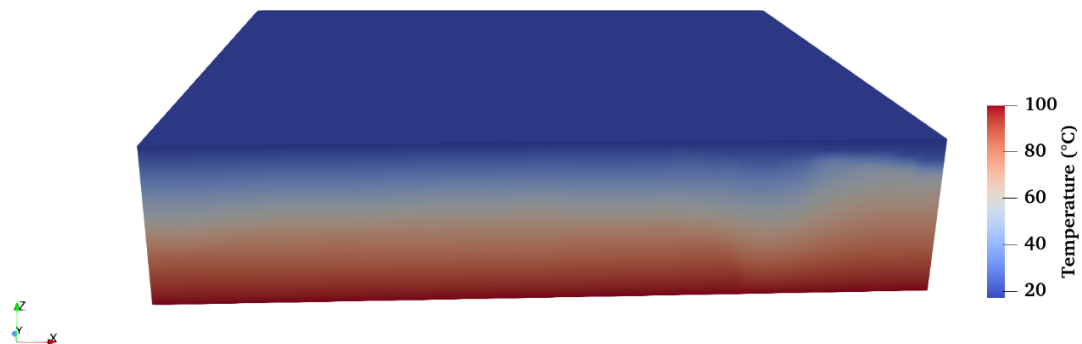


Figure 5. Looking from the south at the temperature distribution in the Underworld3 3D model solution.

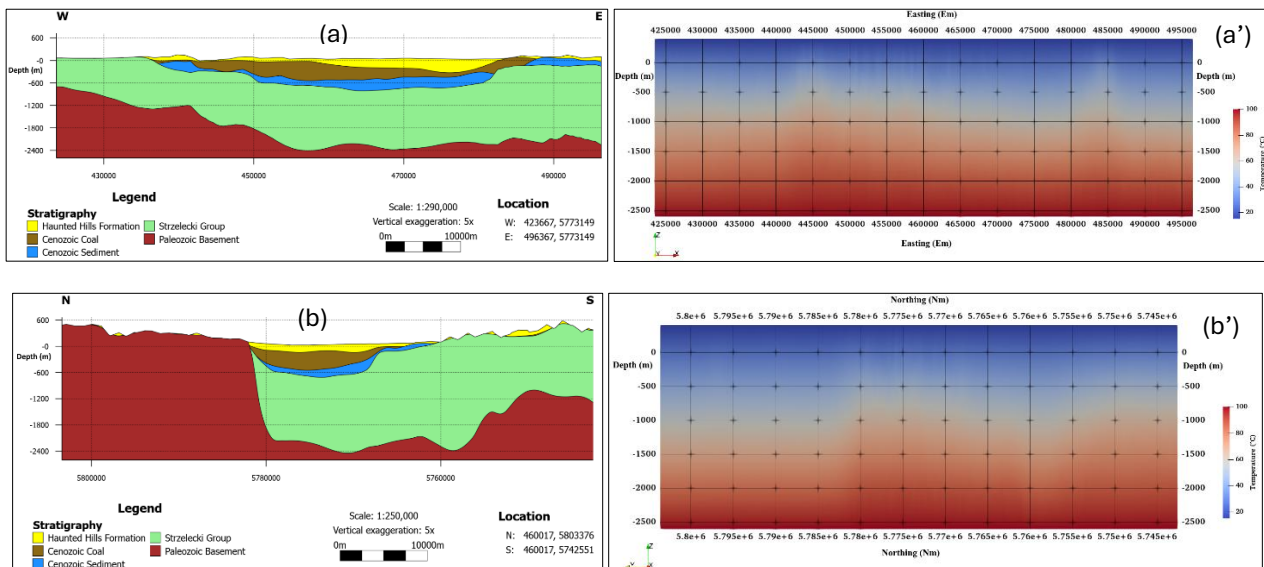


Figure 6. (a) East-west geological cross-section through the model domain showing the stratigraphic framework; (a') corresponding east-west temperature profile displaying elevated temperatures beneath thick coal-bearing units (vertical exaggeration = 8). (b) North-south geological cross-section showing lateral variation in Cenozoic coal and siliciclastic units; (b') corresponding north-south temperature profile illustrating subsurface heat accumulation beneath low-conductivity coal sequences (vertical exaggeration = 8).

Cross-sectional views of the 3D geological and thermal models (Figure 6) reveal a strong impact of the stratigraphic architecture on the subsurface temperature distribution. The geological sections (Figures 6a and 6b) illustrate the lateral continuity of major stratigraphic units, including the Cenozoic coal-bearing formations and the underlying siliciclastic sediments. The accompanying temperature profiles (Figures 6a' and 6b') demonstrate that elevated temperatures occur directly beneath the thickest coal accumulations in the Latrobe Valley, whereas cooler zones coincide with areas where coal seams are thinner or absent. This pattern highlights the pronounced insulating effect of brown coal, which possesses very low thermal conductivity relative to surrounding lithologies. Consequently, heat is trapped within the deeper Cenozoic siliciclastic aquifers, producing localized thermal anomalies favorable for geothermal energy exploitation. These cross-sections confirm that lithological contrasts—particularly variations in coal thickness and lateral facies changes—are the primary controls on conductive heat retention and the spatial distribution of geothermal potential within the onshore Gippsland Basin.

3.2 Heat flow refraction

The distribution of surface heat flow predicted by the model suggests strong spatial variability linked to lithology and basement exposure (Figure 7). The highest heat flow values occur along the western and northern margins, where the Strzelecki Group and Paleozoic basement rocks crop out, indicating zones of enhanced heat escape. Conversely, the lowest heat flow values correspond to the thickest coal-bearing area (Latrobe Valley), consistent with heat refracting around the low thermal conductivity of brown coal sequences (Rawling et al., 2013).

While the actual values of heat flow are artificially constrained by the rigid adoption of a constant temperature basal boundary condition, this pattern suggests that the thermal properties of individual stratigraphic units likely exert significant control over the pathways of conductive heat flow from the interior to the surface of the Earth in the study area. Units characterized by low-conductivity materials (e.g., coal) retard vertical heat flow, leading to elevated subsurface temperatures, whereas regions with high-conductivity lithologies (e.g., basement rocks) facilitate more rapid heat dissipation and cooling of the subsurface.

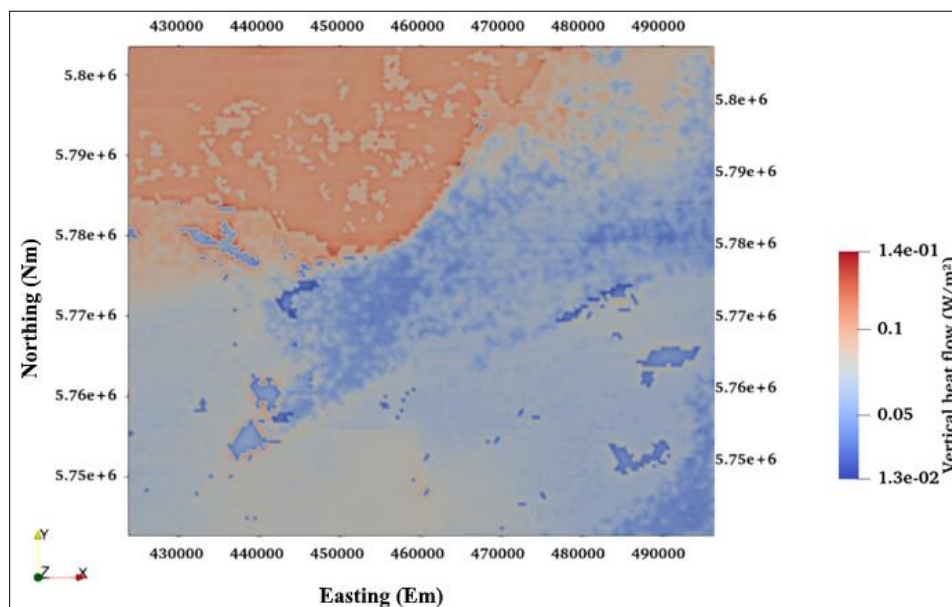


Figure 7. Surface heat flow map produced from the preliminary model.

3.3 Volumetric stored heat

The volumetric method was applied to calculate a preliminary estimate of the heat stored within the target reservoir unit, following the United States Geological Survey (USGS) approach developed by White and Williams (1975). This approach provides a first-order estimate of the total heat in place contained within a defined reservoir volume derived from the 3D geological model. Under the assumption of thermal equilibrium between the rock matrix and pore fluids, and spatially uniform physical properties within each modelled unit, the total stored thermal energy Q_t (J) is calculated as:

$$Q_t = V [\rho_w C_{pw} \phi + \rho_r C_{pr} (1-\phi)] \Delta T$$

where V is rock volume (m^3); ρ_w and ρ_r are densities (kg/m^3) of the pore water and rock matrix, respectively; ϕ is porosity (0–1); C_{pw} and C_{pr} are specific heat capacities ($J/kg.K$) of pore water and rock matrix, respectively; and ΔT is the temperature difference (K) between the rock and the Earth's surface.

For the Cenozoic Sediment layer—the principal geothermal energy target—input parameters listed in Table 2 were derived from the static model and previously published data (Rawling et al., 2011). Using the values from Table 2, the total thermal energy stored in the Cenozoic Sediment formation beneath the study area is estimated to be between 7.45×10^{19} J and 8.16×10^{19} J (≈ 75 –82 EJ), reflecting the uncertainty in formation porosity ($\phi = 0.33$ –0.43).

Table 2. Input parameters for volumetric estimation of stored heat.

	Volume (km^3)	Porosity (%)	Surface Temperature ($^{\circ}C$)	Rock Temperature ($^{\circ}C$)	ρ_w (kg/m^3)	ρ_r (kg/m^3)	C_{pw} ($J/kg.K$)	C_{pr} ($J/kg.K$)
Cenozoic Sediment	~560	33–43	15	67	1000	2200	4180	800

4 CONCLUSION

This study presents an integrated 3D geological and thermal model of a section of the onshore Gippsland Basin that enhances our understanding of its geothermal potential. By combining geological data from prior studies with steady-state heat flow simulations in Underworld3, we established a preliminary picture of the study area's temperature and heat distribution. The results confirm that thick coal-bearing sequences in the Latrobe Valley act as efficient thermal insulators, allowing heat to accumulate within the underlying siliciclastic sediments. The integration of geological and thermal models provides a robust tool for identifying thermally anomalous zones and favorable drilling targets for geothermal resource development in the onshore Gippsland Basin.

The next stages in the assessment will be to further constrain the conductive heat flow model by:

- incorporating laterally varying mean surface temperature,
- defining laterally varying thermal conductivity and heat generation values for each stratigraphic unit, linked to lateral lithological variations.
- defining laterally varying basal temperature at 2.6 km below sea level, inferred from true temperatures reported from groundwater and petroleum bores within the model volume.

The approach developed here can be adapted for other basins across Australia and globally, helping to unlock underutilized geothermal resources and supporting the transition toward a green and sustainable energy future.

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