Forward Prediction of Temperature Distribution Direct From 3D Geology Models

Gibson, H.[1], Stüwe, K.[2], Seikel, R.[1], FitzGerald, D.[1], Calcagno, P. [3], Guillen, A.[1] and McInerney, P.[1]
[1] *Intrepid Geophysics, Unit 2, 1 Male Street Brighton, Victoria, 3186, Australia.*
[2] *Karl-Franzens-University,Universitätsplatz2 A-8010 Graz, Austria.*
[3] *BRGM, 3 Avenue Claude-Guillemin, BP 36009-45060, Orleans Cedex 2, France.*
Email: helen@intrepid-geophysics.com; kurt.stuewe@uni-graz.at; ray@intrepid-geophysics.com; des@intrepid-geophysics.com; p.calcagno@brgm.fr; antonio@intrepid-geophysics.com; phil@intrepid-geophysics.com

ABSTRACT

Work is under way to develop a method for rapid calculation of temperature distribution directly from a 3D geology model. A need for this tool stems from Australia's emerging geothermal energy exploration and production industry. The prohibitive cost and huge task involved in acquiring comprehensive sets of heat flow data, means that the ability to accurately model heat flow at surface, and/or predict 3D temperature distribution for a modelled part of the crust, will be key to supporting this industry. Here we explain the approach we have taken.

INTRODUCTION

Providing a sophisticated way to forward model temperatures from 3D geology models will be possible via the marriage of a new geothermal software module, with an existing 3D model-building application: GeoModeller (developed by Intrepid Geophysics and BRGM). The final module will perform temperature calculations on generic voxet models as well as those built in GeoModeller, but will require GeoModeller as the engine.

Here we present: 1) a summary of the relevant theory of heat flow, 2) an explanation of how it was implemented, 3) justifications for the assumptions and simplifications we currently make for the Australian geological setting, 4) a unit test report from the proto-type code, and 5) a brief overview of the Paralana geothermal energy exploration project (South Australia) – the subject of a 3D geology model being built to validate the new software module.

GEOTHERMAL MODULE DESIGN

Heat transfer: Governing equation

Prediction of 3D temperature and heat flow needs to account for all processes that transfer heat in the Earth's crust (Stüwe, 2007). Whilst there are eight main processes possible (Table 1), typical geological settings throughout Australia allow us to neglect several of these processes.

Firstly, only the production of heat via radiogenic sources usually needs to be considered in the Australian continental setting. This is because no highly active tectonism, metamorphism or volcanism is occurring in the upper crust today, which might otherwise contribute to mechanical or chemical heat production.

Secondly, it is usually sufficient to consider only the case of thermal steady state for the Australian crust. Thermal steady state means there is no change of the temperature distribution over time, i.e., the crust has attained thermal equilibration since the last period of tectonic disturbance.

Table 1. Full list of heat transfer processes, with five that can be ignored for the Australian geological setting shown in italic type.

Heat Transfer Processes	
Conduction of heat	
Production of heat by:	Radioactivity
	Mechanical work (friction)
	Chemical reaction
Advection (Convection) of heat by:	Fluids
	Erosion
	Deformation
	Magma

$$\frac{dT}{dt} = \kappa\nabla^2 + u\nabla + \left(S_{rad} + S_{chem} + S_{mech}\right) / \left(\rho c_p\right) \qquad (1)$$

Equation 1 is the heat transport equation in 3 dimensions, in its full Cartesian form, for material with constant thermal conductivity. T is temperature and t is time. κ is the thermal diffusivity given by $\kappa = k/(\rho c_p)$ where k is thermal conductivity, ρ is density and c_p is heat capacity. u is the advection rate vector. The heat production: S, is here written as the sum of contributions from radiogenic, chemical and mechanical heat sources.

Whilst neglecting some of these heat transfer processes is valid, Equation 1 assumes constant thermal conductivity. For geothermal energy exploration in hot, relatively dry systems (which is the Australian experience, see Beardsmore (2007)), large conductivity contrasts between different rock types are essential to the exploration model. Therefore, the consideration of variable conductivity is a crucial aspect of the modelling.

Equation for the geothermal module

Therefore, the equation of interest to us for providing accurate-as-possible prediction of upper crustal temperature distribution in Australian settings, for the steady state, can be expressed as in Equation 2. Equation 2 combines conduction, advection and heat production terms (for further details see Stüwe (2007)).

$$\left(\frac{d\left(-k\frac{dT}{dx}\right)}{dx} + \frac{d\left(-k\frac{dT}{dy}\right)}{dy} + \frac{d\left(-k\frac{dT}{dz}\right)}{dz} \right) + \rho c_p \left(u_x \frac{dT}{dx} + u_y \frac{dT}{dy} + u_z \frac{dT}{dz} \right) = -S \qquad (2)$$

Equation 2 describes the steady state 3D temperature field under consideration of spatially variable thermal conductivity. This is the equation currently solved by our proto-type geothermal module. For definition of terms see Equation 1.

Implementation

In order to make use of Equation 2 in GeoModeller, equation 2 was discretised with an explicit finite difference scheme. This method of solution allowed us to make use of the existing Cartesian voxelised grid of GeoModeller. This finite difference approximation was iteratively solved with a Gauss-Seidel iteration scheme until the sum of the residual errors was small. For a series of effectively one-dimensional unit tests (see below) a solution was obtained for a 20 x 20 x 20 voxelised grid within about 1 minute using a standard PC.

However, for larger voxelised grids the calculation time would increase rapidly. We are therefore considering implementing an explicit multi-grid algorithm which best operates on a grid with a power of 2 number of nodes in each spatial direction. This algorithm only operates on the errors of the previous solution, making it a very efficient tool to handle 3D heat flow. In further plans we will also consider solving the equations of heat transfer on a properly triangulated finite element mesh which will enable much better handling of problems involving topography at the surface and the full use of GeoModellers main strength: the powerfully interpolated surfaces separating rock types of spatially variable thermal and other physical properties.

Boundary conditions

As with any differential equation, the derived equation for 3D temperature prediction needs boundary conditions to evaluate the integration constants. On the 4 vertical sides, it is assumed that no heat flows through the model boundaries (i.e., Neuman type boundary conditions). This implies that all lithologies and *in-situ* temperatures are mirrored beyond the model boundaries. At the base, either a heat flow or a constant temperature may be applied. Finally, at the top a constant temperature is applied for which we have initially assumed zero °C, but any mean annual temperature can be prescribed there.

Topography effects

Allowing for topography is a key concern for accurate prediction of 3D temperature distribution, as illustrated in Figure 1 where temperature distribution is highly influenced by topography in the shallow sub-surface, and is less influenced at depth.

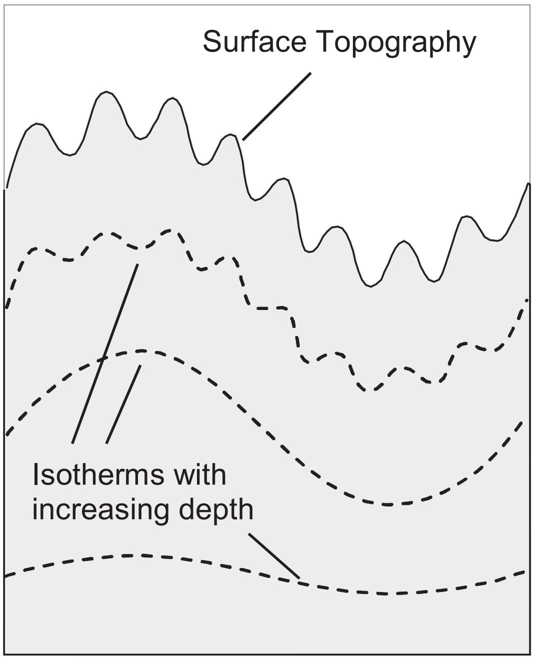

Figure 1. The influence of surface topography on isotherms at depth (after Stüwe K. and Hintermüller M., 2000).

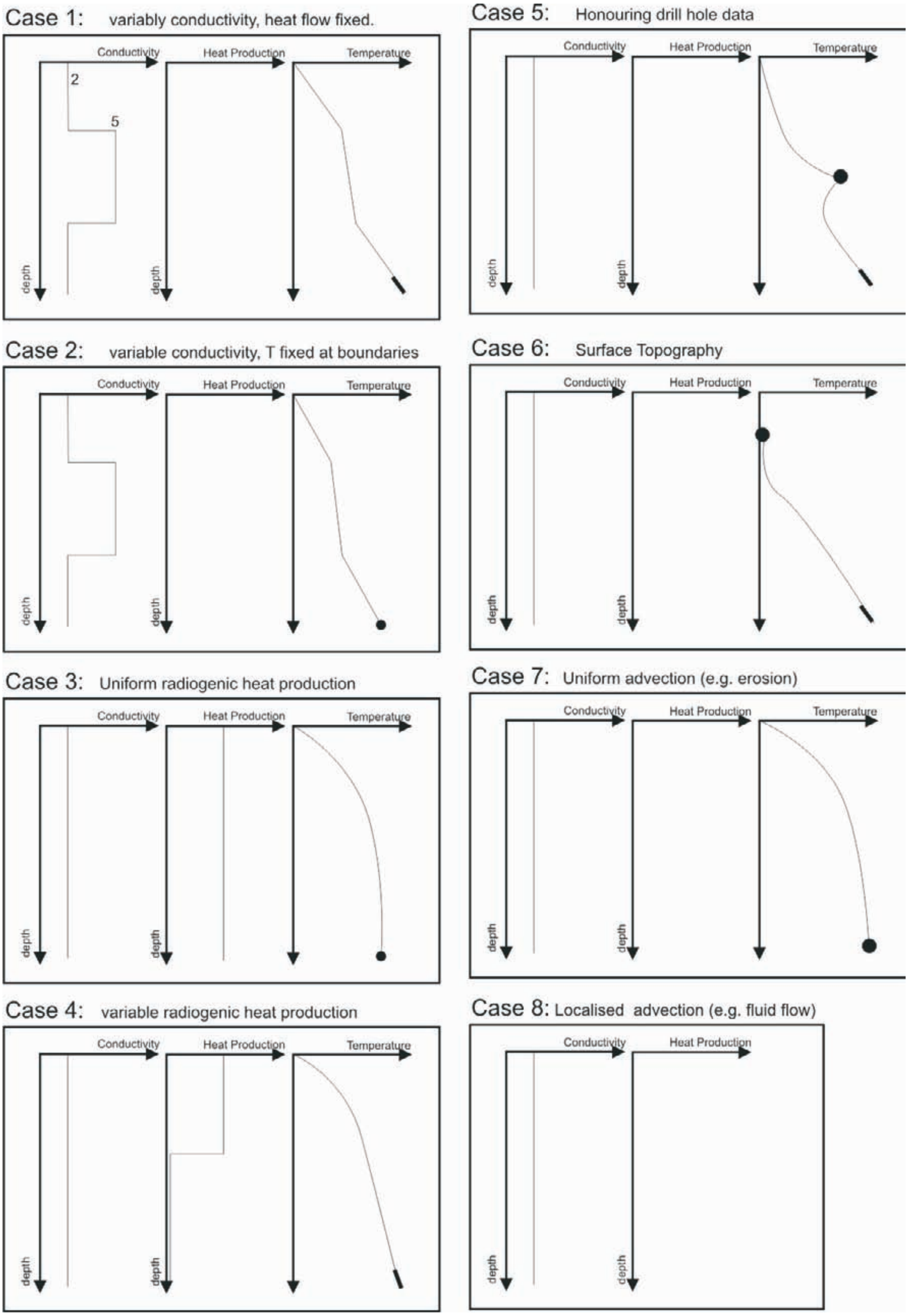

Figure 2. Cartoons illustrating the essence of the unit tests applied to the proto-type geothermal module performing forward 3D temperature modeling.

UNIT TEST RESULTS

In order to test our finite difference approximation, 8 unit tests were performed with the proto-type geothermal module, using different initial settings and boundary conditions (Table 2). The overall design of these tests is illustrated in Figure 2.

All 8 tests passed, as verified by returning the expected pattern of temperature distribution, and by independent analytical solutions where it was possible to derive them. Results are shown in Figure 3, where they are presented in the form of voxelised, 2D temperature distributions rendered to a vertical section cutting the original 3D geology model.

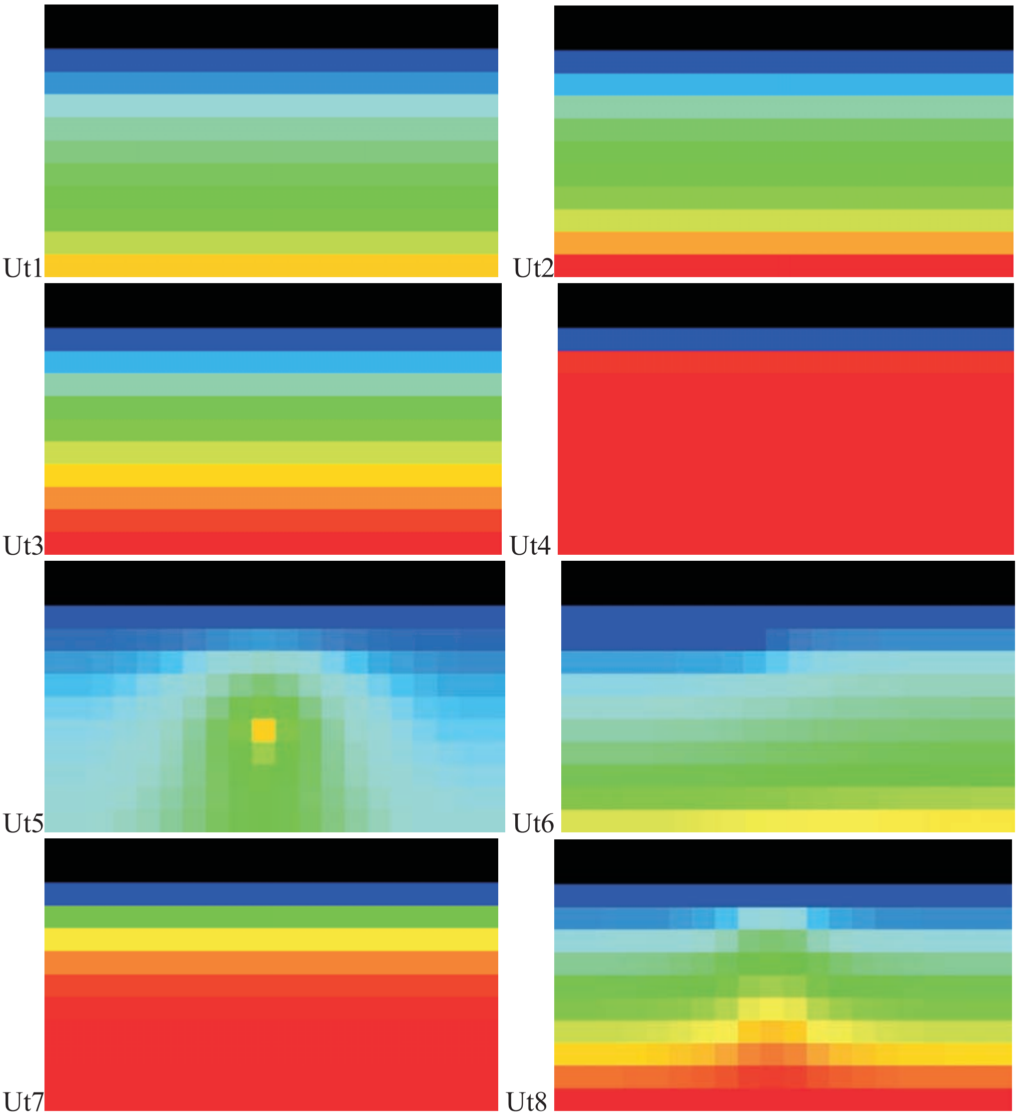

Figure 3. Unit test results: 2D sections rendered from 3D solutions predicting temperature variation for the 8 unit tests. See Table 2 and Figure 2 for test details.

Unit Test	Case Name	Conductivity	Heat Production	Bottom boundary condition
1	Initial condition 1	Variable conductivity (in 3 layers: k = 2, k = 5 and k = 2)	none	constant heat flow
2	Initial condition 2	Variable conductivity (in 3 layers: k = 2, k = 5 and k = 2)	none	constant temperature
3	Initial condition 3	constant conductivity	constant heat production	constant temperature
4	Initial condition 4	constant conductivity	Step-shaped distribution of heat production	constant heat flow
5	Honouring drill hole data	constant conductivity	none	constant temperature
6	Honouring topography	constant conductivity	none	constant heat flow
7	Uniform advection	constant conductivity	none	constant temperature
8	Localised advection	constant conductivity	none	constant temperature

Table 2. The initial settings and boundary conditions for 8 unit tests designed to validate the proto-type geothermal module.

PARALANA CASE STUDY

The Geological Setting

Petratherm Ltd is actively exploring for heat, and thus a viable geothermal energy source in the Poontana Graben, northern Flinder's Ranges (South Australia). Their deepest well to date, Paralana-1B, reveals temperatures of ~109 °C at 1,806 m (Figure 4) and 2D temperature modelling of the project area indicates they can expect temperatures of 200 °C at 3,600 m.

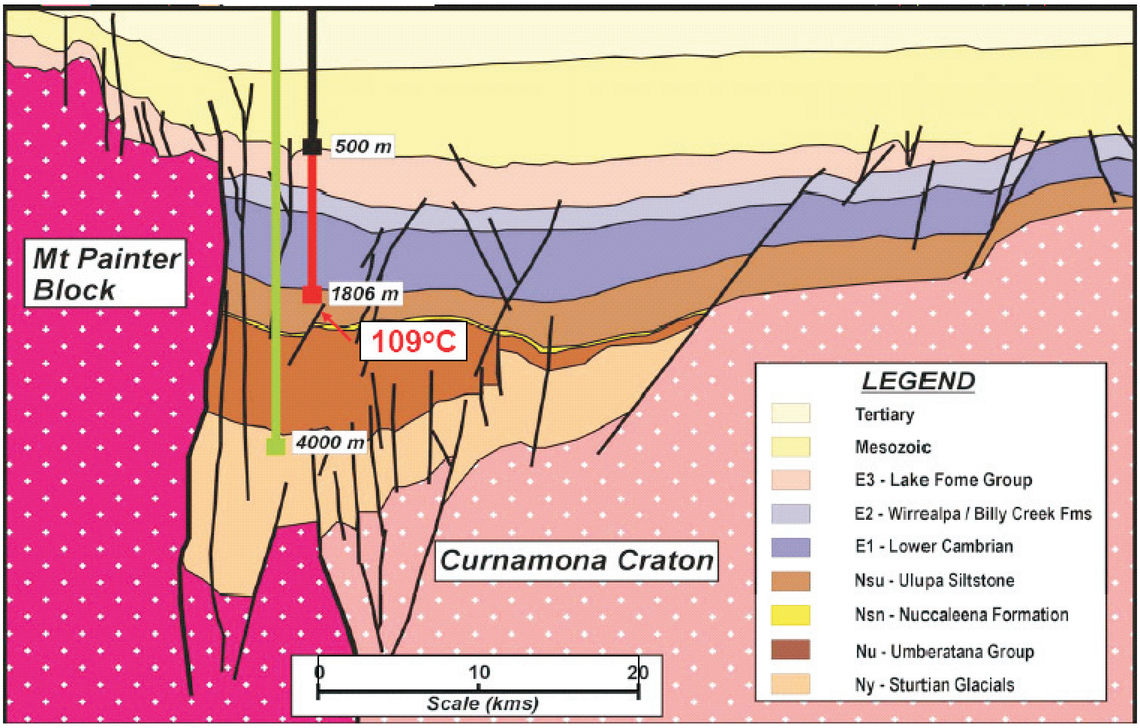

Figure 4. Generalised west-east cross-section through the Poontana Graben, northern Flinders Ranges, South Australia.

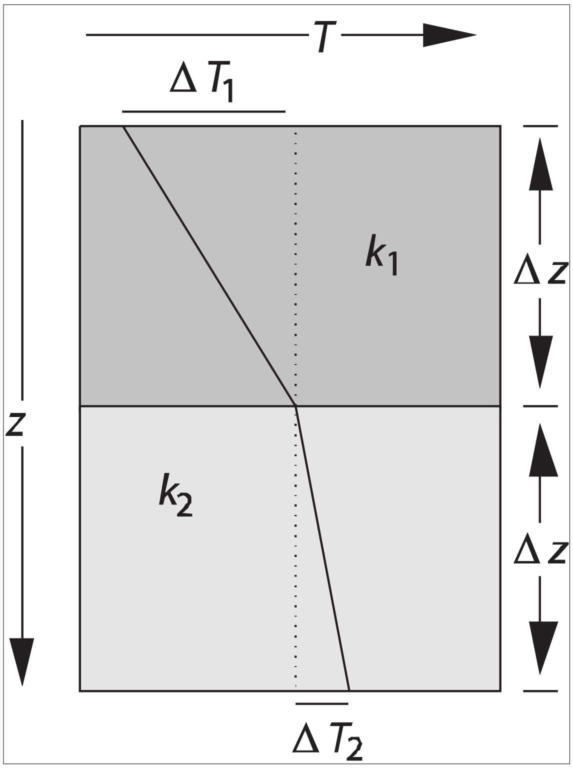

Figure 5. The principle of heat refraction in the crust.

The geothermal energy exploration model

Different thermal gradients will exist in rock units of different conductivity and this is the essence of the typical geothermal energy resource in Australia. As well as other key factors including an ability to enhance natural fractures at depth (to create a circulating system), finding a viable heat resource requires abnormally high rock temperatures close to the surface. In Australian settings, this is most easily achieved near radiogenic granites (with high thermal conductivity), where a sedimentary cover of low thermal conductivity lies above (a thermal insulator). This situation sets up heat refraction in the crust and delivers high temperatures to shallow depths (Figure 5).

At the Paralana Project, radiogenic granites of the Mt Painter Block are providing a high heat flow, which is being blanketed mainly by Cambrian sediments of the Arrowie Basin (units E3, E2 and E1 in Figure 4).

Work is currently underway to build a 3D geology model of the Paralana project in 3D GeoModeller. This model will be used to verify the new software module.

FINAL COMMENT

A planned initiative by Geoscience Australia is to provide and maintain a database of measured heat flow, rock types, thermal conductivities, etc., for geologic terrains throughout Australia. This will be a key information resource for explorers in the geothermal energy industry, greatly assisting the targeting of locations containing shallow, anomalously high heat reserves. Our view is that the database will usefully contain both observed and predicted temperature data. Therefore, we believe our work in developing an accessible method for rapid calculation of temperature distribution directly from 3D geology models, makes a valuable contribution to this initiative.

ACKNOWLEDGEMENTS

This project is partially funded by the South Australian Government through the Australian Geothermal Energy Group's (AGEG) Tied Grant for Geothermal Research Hub (Technical Interest Group 9).

Intrepid Geophysics also acknowledges support of this project from Geoscience Australia (GA) and Petratherm Ltd.

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