EXTENDED ABSTRACT SUBMISSION

20th International Geophysical Conference and Exhibition
Adelaide, South Australia
22-25 November 2009

DEADLINE FOR SUBMISSION FOR REVIEW – Friday 26 September 2008

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FORWARD PREDICTION OF SPATIAL TEMPERATURE VARIATION FROM 3D GEOLOGY MODELS

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Keywords: Geothermal, temperature, heat flow, 3D geology, steady state, voxet models, GeoModeller software, unit test, Mt. Painter.

OVERVIEW

Collaborative work is under way to develop an accessible method for rapid calculation of the spatial variation of temperature directly from a 3D geology model. The need for a tool of this nature 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 and possibly others. Here we explain the approach we have taken. The Mount Painter region in South Australia is used as a case study to showcase the developments.

INTRODUCTION

This extended abstract presents: 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 built to validate the technique.

Providing a sophisticated way to forward model temperatures from 3D geology models is possible via the marriage of the new geothermal software module, with an existing 3D model building application: *GeoModeller* (developed by BRGM and Intrepid Geophysics). The advantage of using GeoModeller is that it enables fully-3D geology models to be rapidly built from diverse datasets and observations. Therefore high accuracy is possible when predicting the final temperature distributions. The temperature calculations can also be made on generic 3D voxet models as well as those built in GeoModeller.

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 (Table 1), we propose that typical geological settings throughout Australia allow us to neglect several of these.

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*

Table 1. The eight main processes of heat transfer (after Stüwe, 2007). The five that can be ignored for the Australian geological setting are shown in italic type.

Firstly, we propose that only the production of heat via radioactive 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.

Heat Transport Equation

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

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 advection rate vector. The heat production: S, is here written as the sum of contributions from radiogenic, chemical and mechanical heat sources.

Equation 1. The heat transport equation in 3 dimensions, in its full Cartesian form, for material with constant thermal conductivity (after Stüwe, 2007).

Secondly, we propose that it's 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.

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

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, which combines conduction, advection and heat production terms (for further details see Stüwe, 2007).

Equation for 3D temperature prediction

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

Equation 2. Equation for the steady state 3D temperature field under consideration of spatially variable thermal conductivity (after Stüwe 2007). This is the equation currently solved by our proto-type geothermal module. For definition of terms see Equation 1.

Implementation

Equation 2 was discretised with an explicit finite difference scheme in order to make use of it in GeoModeller. 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 GeoModeller's 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.

For the entire bottom boundary of the model, we have currently implemented code to apply either constant heat flow, or constant temperature. We suggest this treatment will be satisfactory in most scenarios and in any case, it would be unusual to have extensive constraints on temperature variability for a surface at depth. If there is evidence for basal boundary temperature variability, then we might suggest that a more meaningful treatment is to increase the vertical extent of the model, rather than implement a spatially variable bottom boundary condition.

Finally, at the top boundary, a constant temperature is applied. For this we have initially assumed 0°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. Surface topography is dealt with by defining the air / solid geology interface in the model (e.g. via a digital elevation model). Demonstration of successful accounting for topography effects on temperature distribution, during initial unit testing, is given below (see Figure 3, Case 6).

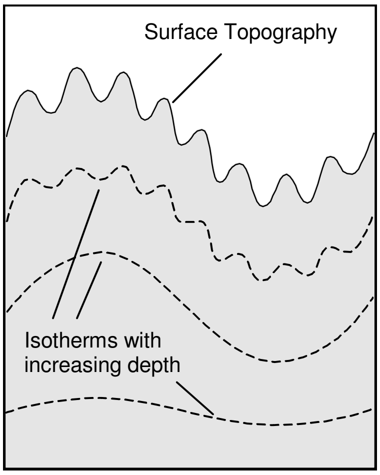

Figure 1. The influence of surface topography on isotherms at depth (after Stüwe K. and Hintermüller M., 2000)

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 below 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 voxelized, 2D temperature distributions rendered to a vertical section cutting the original 3D geology model.

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

Table 2. The initial settings and boundary conditions for 8 unit tests (Cases 1–8) designed to validate the proto-type geothermal module.

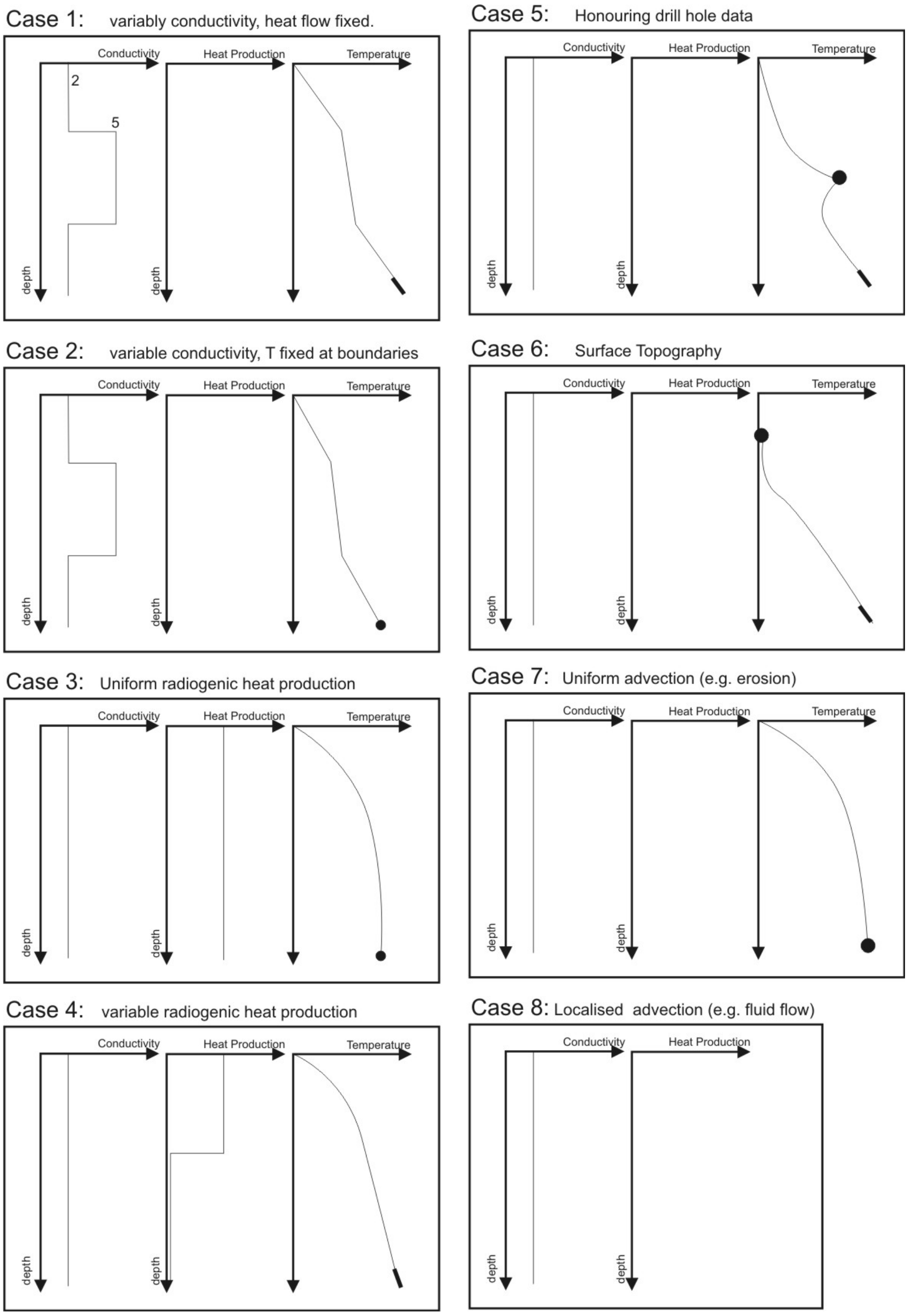

Figure 2. Cartoons illustrating the essence of the unit tests applied to the proto-type geothermal module performing forward 3D temperature modeling.

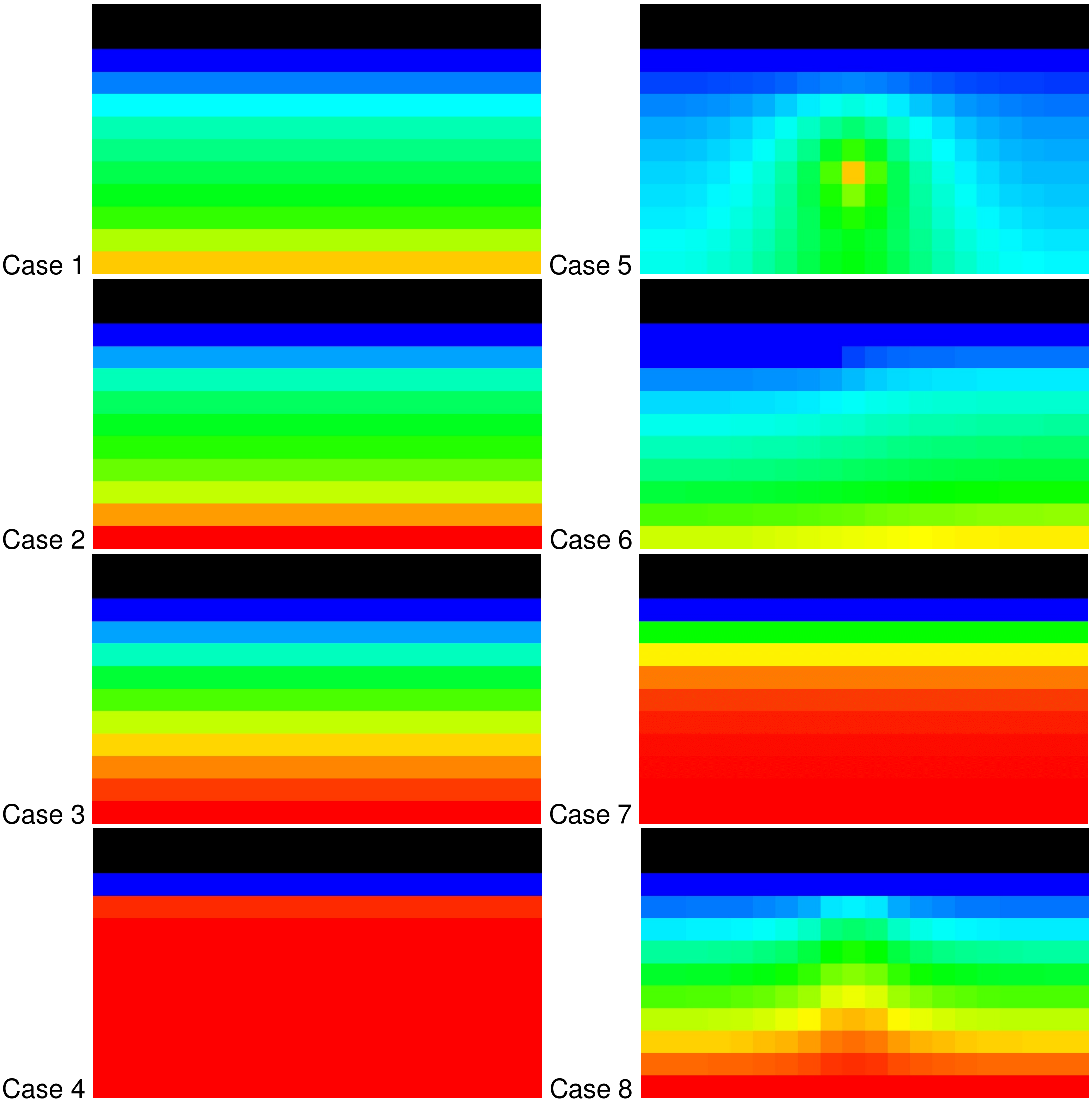

Figure 3. Unit test results for Cases 1 to 8: 2D sections rendered from 3D solutions predicting temperature variation for each case. See Table 2 and Fig. 2 for case details. Legend details: Red is maximum and blue is minimum, colours between are at linear intervals. For Cases 1, 4 and 6 the temperature range is 0 to 6 °C; for Cases 2, 3, 7 and 8 the temperature range is 0 to 100 °C; and for Case 5 the temperature range is 0 to 50 °C.

PARALANA CASE STUDY

The geological setting

The Paralana Project area lies about 20 km east of the outcropping ranges of Mt Painter, in northern South Australia. Outcrop mapping, drill holes and seismic survey data suggest that surficial Tertiary and Mesozoic units in this area overlie sedimentary rocks of the Cambrian Arrowie Basin which include red bed sequences of the Lake Frome Group, and thick consolidated units of Hawker Group sandstone, shale and limestone (Fig. 4). These in turn overlie thick Adelaidean rocks of the Wipena, Umberatana, Burra and Callana Groups.

The geothermal energy exploration model

Petratherm Ltd is actively exploring for heat, and thus searching for 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 1806m (Fig. 4). 2D temperature modelling of the project area indicates they can expect temperatures of 200°C at 3600m.

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 radioactive granites (with high thermal conductivity), where a sedimentary cover of low thermal conductivity lies above and acts as a thermal insulator. This situation causes a change in geothermal gradient, and delivers high temperatures to shallow depths (Fig. 5).

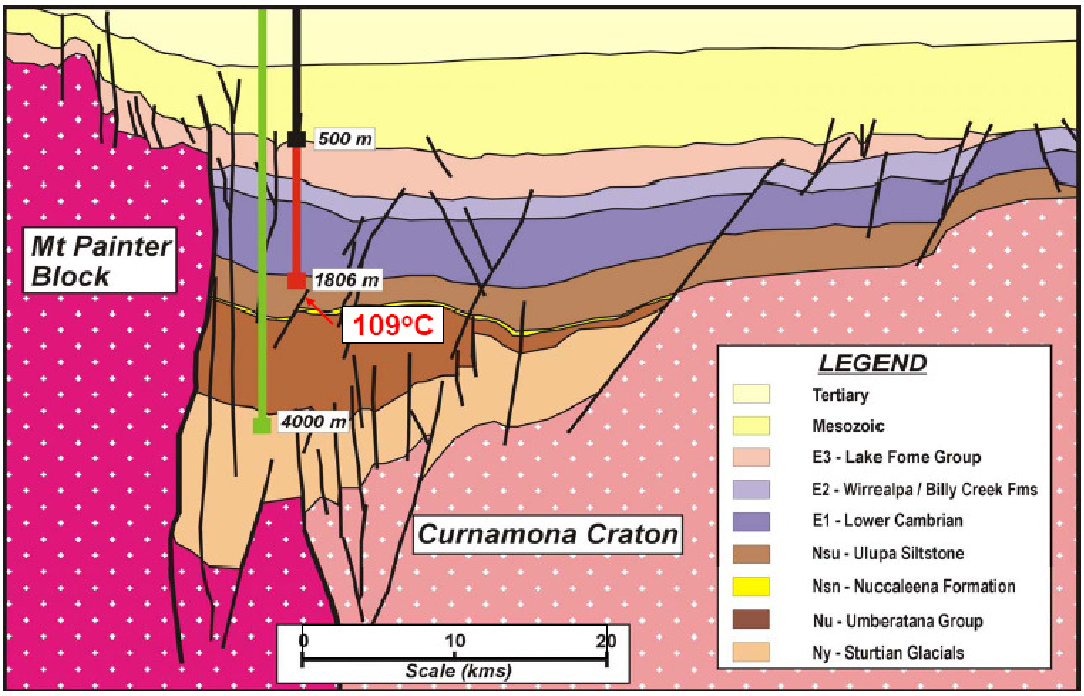

Figure 4. Generalised west-east cross-section through the Poontana Graben, northern Flinders Ranges, South Australia. E1 - E3 are sedimentary rocks of the Cambrian Arrowie Basin; Nsu, Nsn, Nu, Ny are sedimentary rocks of the Pre-Cambrian Adelaidean sequence (source: Petratherm Ltd.)

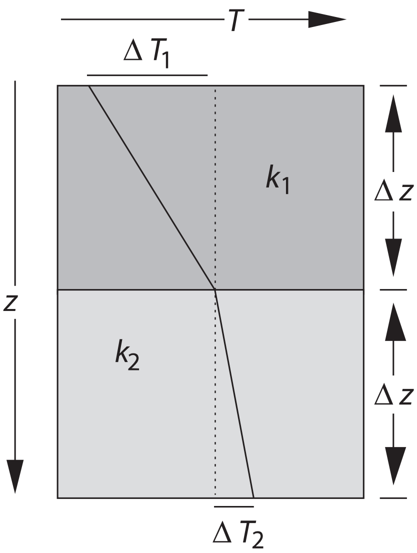

Figure 5. Cartoon illustrating how the geothermal gradient changes with depth if a low conductivity layer (k1) overlies a high thermal conductivity layer (k2). This is a special case of what is more generally known as heat refraction. Source: Stüwe 2007

At the Paralana Project, radioactive 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 Fig. 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 by predicting the 3D temperature distribution and comparing the results with directly measured formation temperatures.

CONCLUDING COMMENT

Geoscience Australia's planned initiative to provide and maintain a database of measured heat flow, rock types, thermal conductivities, etc., for geologic terrains throughout Australia, will be a key information resource for explorers in the geothermal energy industry. These data will greatly assist the targeting of locations containing shallow, anomalously high heat reserves. Our view, and that of Geoscience Australia, 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 specific 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 gratefully acknowledges Petratherm Ltd. for the use of Paralana project data, and also acknowledge GeoScience Australia (GA) for their commitment and ongoing support. The authors thank Graeme Beardsmore for helpful and constructive review comments.

REFERENCES

Beardsmore G, 2007. Geothermal energy potential of the Northern Territory. *Northern Territory Geological Survey, Record* 2007-004.

Stüwe K. 2007. Geodynamics of the Lithosphere. An Introduction. 2nd edition. Springer Verlag 493 pages

Stüwe K. and Hintermüller M., 2000. Topography and isotherms revisited: The influence of laterally migrating drainage divides. Earth and Planetary Science Letters, vol 184, p. 287-303.