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Practical Aspects of 3D Temperature and Heat Flow Modelling for EGS Energy Exploration Including a High Relief Terrain Case Study

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ABSTRACT

Key to accuracy in temperature and heat flow modelling is the ability to make calculations directly from well-constrained 3D geology models (Gibson et. al. 2008, Meixner and Holgate, 2008). Correct treatment of topography is another key concern for modelling heat flow patterns which replicate those measured in the real world (Stüwe and Hintermüller, 2000; Braun, 2003).

Commencing with a synthetic 3D geology model, featuring high topographic relief and variable scenarios of thermal conductivity contrasts, we present results from thermal modelling employing an explicit finite difference method to solve for temperature in the steady state. Our solver scheme populates a Cartesian voxelised grid with resulting in-situ temperatures, heat flow values and temperature gradients.

Our synthetic model is a test-bed for the Köflach district of Eastern Austria for which a *3D GeoModeller*[1] geology model is currently under construction. The Köflach model will demonstrate realistic 3D temperature and heat flow modeling, verified against measured insitu temperatures and heat flow data, whilst always obeying topographic effects. The existence of thermally insulating lignite beds at Köflach lends itself as a possible analogue for Enhanced Geothermal System (EGS) plays which also typically require the existence of shallow insulating horizons to setup a scenario of anomalously high heat occurrence, at accessibly shallow depths. This work also has implications for geothermal energy exploration in Eastern Australian's coal-bearing basins.

1. INTRODUCTION

This extended abstract presents: 1) a review of heat flow modeling in GeoModeller including the simplifications, assumptions and boundary conditions employed; 2) explanations and derivations of the temperatures and other outputs written to 3D voxets; 3) presentations of results from a synthetic geology model featuring high topographic relief and variable thermal conductivity contrasts; and 4) an introduction to the geology of Köflach, Eastern Austria and a description of the aims and objections of this case study which is now underway.

2. HEAT MODELLING IN 3D GEOMODELLER

An accessible method for rapid calculation of the spatial variation of temperature, heat flow and geothermal gradients - directly from a complex 3D geology model – is now available within *3D GeoModeller*. This software (developed by BRGM and Intrepid Geophysics) is well renowned for it's ability to model sophisticated geology in association with detailed digital elevation models (DEMs), and now also recently provides a geothermal module.

The solved equation in GeoModeller combines terms that account for conduction, heat production and advection (Stüwe, 2007). See Table 1. Furthermore, the equation solves for the steady state 3D temperature field under consideration of spatially variable thermal conductivity. Implementation of the heat transport equations in *GeoModeller* is covered in previous work by Gibson et. al. 2008.

Table 1: Of the main processes of heat transfer (centre) three of these (diffusion, radioactive decay, and advection by fluids) are accounted for in GeoModeller because together they contribute the majority of measurable heat in settings devoid of significant present-day tectonism, seismicity, metamorphism or volcanism

Mode of heat transfer	Process	Accounted for in 3D GeoModeller
Conduction	Diffusion	Yes
Heat Production	Radioactive decay	Yes
	Mechanical work (friction)	No
	Chemical reaction	No
Advection	Fluids	Yes, simple[1]
	Erosion	No
	Deformation	No
	Magma	No

[1]*Currently only one dimensional scenarios involving advection of heat by fluids can be solved in GeoModeller but development is on-going.*

The solver currently adopts an explicit finite difference approximation scheme that has the advantage of being able to utilize a readily-prepared Cartesian voxelised grid from the smooth 3D geology model. (Note that model-voxelisation is also need for geophysical inversion, but is a simplification of GeoModeller's normal operational mode that uses a potential field method to calculate smooth 3D geology boundaries from contact and orientation data.)

For 3D temperature, finite difference approximation is solved with a Gauss-Seidel iteration scheme continuing until one of the following occurs: Either the sum of the residual errors is smaller than the user-defined maximum value (maximum change in temperature in any one cell, from one iteration to the next), or a user-defined number of iterations has been performed (where one iteration is defined to have occurred when the solver has acted in every voxel).

3. TOPOGRAPHY AND BOUNDARY CONDITIONS

In solving for temperature *GeoModeller* honors all thermal boundary conditions, and any known temperatures (fixed) that are internal to the project (e.g. temperature well-logs).

As illustrated in Figure 1 (after Stüwe and Hintermüller, 2000) and demonstrated by our results below, topography is a key concern for accurate 3D temperature prediction (also Braun, 2003). Treatment of topography during thermal modeling can approach (but not equal) the detail of the original DEM by ensuring fine resolution in the discretization scheme.

Currently, a constant surface temperature is applied at the topography boundary, but soon constant heat flow will also be an option. This will be a useful improvement, because measured heat flow values can then define the upper boundary rather than an assumed surface or paleo-surface temperature. Working exclusively with heat flows in this way can negate the concern for a dis-equilibrium state so one can concentrate on "heat in the system now", regardless of it's thermal equilibration status.

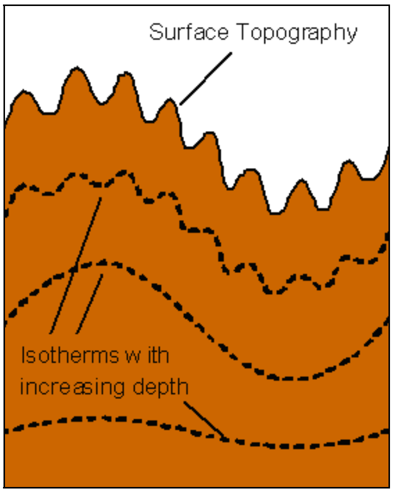

Figure 1: Schematic illustration of the influence of surface topography on isotherms showing that temperature distribution is highly influenced by topography in the shallow-subsurface, and less influenced at depth (after Stüwe K. and Hintermüller M., 2000).

On the four vertical sides of the geology model, Neuman type boundary conditions apply. That is, it is assumed that no heat flows through the model boundaries (i.e.,). This implies that all lithologies and in-situ temperatures are mirrored beyond the model boundaries (zero heat flow).

Either constant heat flow, or constant temperature is applicable to the bottom boundary of the model. We suggest this treatment is satisfactory in most scenarios, but if there is evidence for variability, then a more meaningful treatment may be to expand the vertical extent of the model, into depth zones where isotherms are predicted to flatten-out (as is the conventional approach taken amongst many modelers), rather than implement a spatially variable boundary condition.

4. 3D TEMPERATURES AND OTHER OUTPUTS

The solver in GeoModeller populates a Cartesian voxelised grid (.vo format) with estimated in-situ temperatures, heat flow values, and temperature gradients. Output values are valid for the center-point of the given cell/voxel. Derivations of outputs are given in Table 2, below.

Table 2: Definitions and derivations of solved values for temperature, heat flow and geothermal gradients as implemented in GeoModeller

3D temperature and other outputs in GeoModeller	
Temperature	(°C) Solved for every cell/voxel centre by Finite Difference approximation
Vertical Heat Flow	(Wm^{-2}) Flow of heat measured in energy per time per unit area. Solved for each cell/voxet centre with respect to the centre of the cell immediately above.
Vertical Temperature Gradient	($°Ckm^{-1}$) Change of temperature over a distance. Solved for each cell/voxel centre with respect to the centre of the cell immediately above.
Total Horizontal Temperature Gradient	($°Ckm^{-1}$) Change of temperature over a distance of one cell to 4 neighbours in the horizontal plane. Equal to the square root of the sum of the squares of the horizontal temperature gradients in the x and y directions. (An expression of gradient strength with no expression of direction within the horizontal plane.)

5. TEST-BED TEMPERATURE MODELLING

5.1 Synthetic Geology Model and Forward Run Set-up

Figure 2 shows our Synthetic geology model built in GeoModeller. The model features topographic relief of up to 7,500m and comprises two geologic units with a simple conformable relationship.

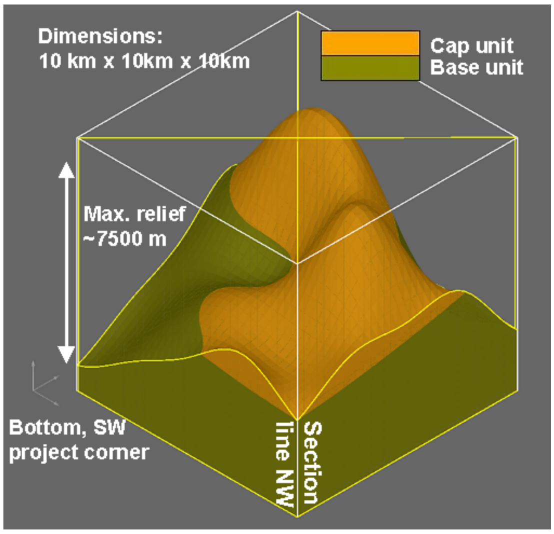

Figure 2: Synthetic solid geology model showing project extents and the maximum topographic relief. The intersection of the DEM with the project bounds are shown in yellow. The model comprises two geology units with a conformable relationship.

Discretization of the smooth geology model in figure 2 followed a scheme by which 100 cells where created in the x, y, and z directions, and hence (dividing these by the model dimensions in Figure 2) the cell sizes were 100m, square. Total number of voxels was therefore 1,000,000.

The mean thermal rock properties listed in Table 3 for each geology unit were applied to the discretized model. A constant heat production rate was used, but thermal conductivities of the two units were varied in the execution of three separate forward runs.

Set boundary conditions for all 3 runs were: 20ºC for the topography surface, and 0.03 Wm^{-2} for the bottom of the model. Maximum iterations were set at 20,000 and maximum residual tolerance was set at 0.0001ºC. Heat capacities were assumed constant at 1000 J kg °C.

Table 3: Thermal rock properties of the geology units in the Synthetic model, for 3 forward runs estimating temperature, heat flow and gradients

Geology unit	Physical properties:	
Run #	Thermal conductivity W m^{-1}K^{-1}	Heat production rate Wm^{-3}
Cap unit		
Run 1	1.5	3.0 x 10-6
Run 2	3	3.0 x 10-6
Run 3	1	3.0 x 10-6
Base unit		
Run 1	3	3.0 x 10-6
Run 2	3	3.0 x 10-6
Run 3	5	3.0 x 10-6

Three thermal modeling runs of the Synthetic model were executed. The set-up parameters for all runs were identical except for the thermal conductivities (TC) of the two geology units (see Table 3). Run 1 explored a moderate degree of TC contrast between the capping unit and the underlying geology, Run 2 explored the effects of no TC contrast, and Run 3 explored a strong TC contrast (Table 3).

5.2 Results of Test-Bed Modelling

3D temperatures predicted in Run 1, are shown in Figure 3. Clearly, the strong topographic relief of the geology model has had a dominating effect on temperature distribution. The temperature range of the 3D voxet for Run 1 is 20.0 to 76.2°C (Table 4). This range is little different for Run 2 (the case of no TC contrast), but ~16°C wider than the temperature range for Run 3 (strong TC contrast).

Temperature results are further displayed in 2D in Figure 4 where again the strong impact of topography on temperature distribution is evident in all runs. Note the asymetry of the heat distribution (in all runs) whereby temperatures are raised shallower in the section below the more gently sloping shoulder of the mountain (right-side of figures), but pushed down in proximity to the highly sloped shoulder (left-side of figures).

Additionally, increased heating of the section at, and below, the capping unit is noted in Runs 1 and 3, as expected, due to the low TCs assigned to this unit (hence a thermally insulating layer) in combination with higher TCs in the units below.

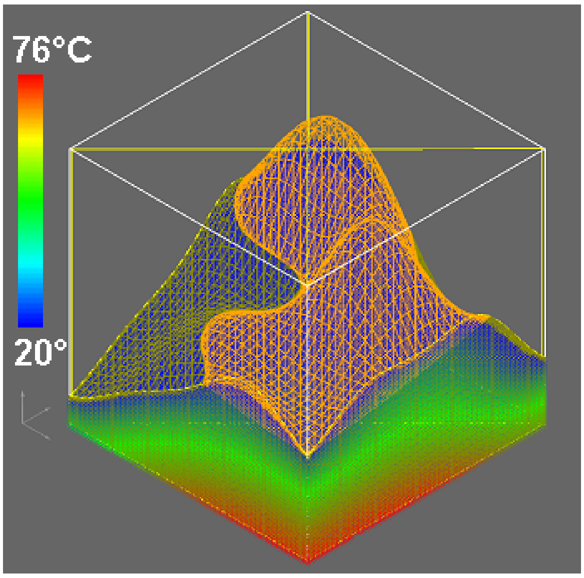

Figure 3: Run 1, 3D temperature voxet (1 million nodes) imported to the synthetic geology model space in GeoModeller. Visual-cut off of the mesh was set to 20.5ºC to allow the topography wire-frame to be viewed (All airspace is otherwise 20ºC, obeying the surface boundary condition.).

Results of vertical heat flow for the 3 runs are given in Table 4 and Figure 4. By range they are: 0 - 0.389, 0 - 0.382 and 0 - 0.388 Wm^{-2} respectively. Compared with world-wide surface heat flows (generally between 0.030 and 0.120 Wm^{-2}) the ranges include extremely high values, but we caution that the distributions are skewed to the lower values in all runs (mostly <0.040 Wm^{-2}). Very high values of modeled heat flow only occur where extreme topography has played a part in juxtaposing very high temperature rocks near surface in a deeply incised valley location, in the synthetic model. (See Figure 4, 2nd row).

Table 4: The resulting ranges for temperature, heat flow and geothermal gradients, as solved in 3D for the Synthetic geology model, in three independent forward thermal modeling runs

3D voxet results by range – Synthetic model			
	Run 1	Run 2	Run 3
Temperature (°C)	20.0 - 76.2	20.0 - 73.1	20.0 - 57.0
Vertical Heat Flow (Wm^{-2})	0 - 0.389 (most <0.040)	0 - 0.382 (most <0.040)	0 - 0.388 (most <0.040)
Vertical Temperature Gradient (°Ckm^{-1})	0 - 128.3 (most <20)	0 - 127.4 (most <20)	0 - 77.7 (most <10)
Total Horizontal Temperature Gradient (°Ckm^{-1})	0 - 80.9 (most <15)	0 - 80.3 (most <15)	0 - 60.1 (most <10)

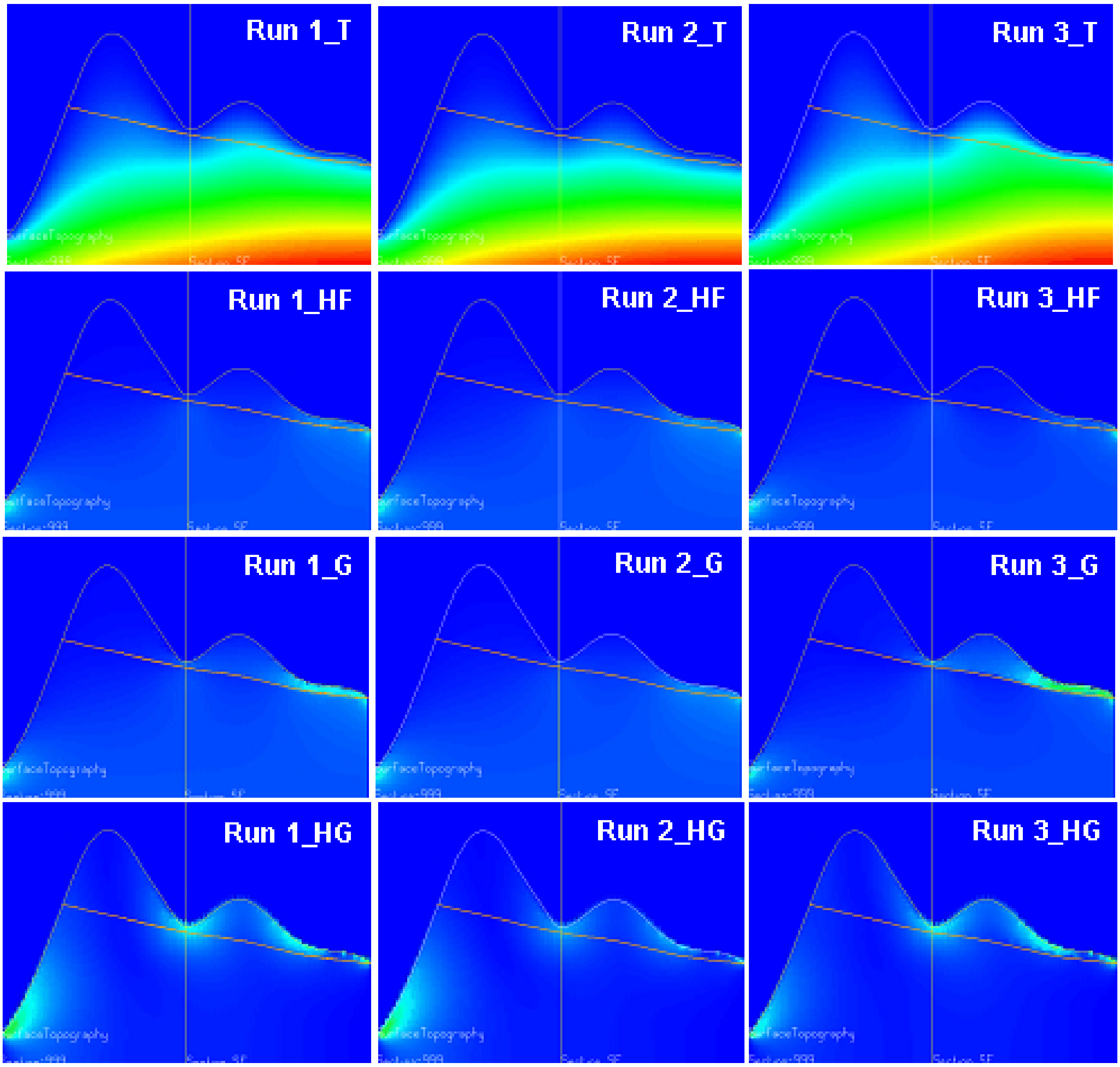

Figure 4: 2D results derived from the 3D voxets, for Section Line NW of the synthetic model (see Figure 2). The left column shows results for Run 1, the centre column are results from Run 2, and the right column are results from Run 3. (T=temperature, HF=vertical heat flow, G=vertical temperature gradient, HG=total horizontal temperature gradient) The set-up parameters for all runs were identical except for the TCs of the two geology units which vary (see Table 3). An outline of the intersection of the DEM with section Line NW is shown in every panel. Also shown is a line representing the geology boundary in the synthetic model.

Vertical temperature gradient results for the 3 runs are given in Table 4 and Figure 4 (3rd row). By range they are: 0 - 128.3, 0 - 127.4 and 0 - 77.7°Ckm^{-1} respectively. Similarly, large modelled ranges have resulted, but again most values are skewed to a lower range (<20°Ckm^{-1}).

Total horizontal temperature gradient results are shown in the bottom row of Figure 4 above, with ranges given in Table 4 (0 - 80.9, 0 - 80.3 and 0 - 60.1°Ckm^{-1} respectively in runs 1, 2 and 3). Again large modelled ranges have resulted, but most values are skewed to lower ranges (see table 4).

For the synthetic model, the highest vertical temperature gradients, and the highest total horizontal gradients occur: a) in shallow sub-surface areas where increased heating at and below the capping unit has occurred due to low TCs of this unit in combination with a contrasting higher TC in the underlying unit (Runs 1 and 3), and b) where extreme topography has caused juxtaposition of high temperature rocks near surface in a deeply incised valley (locations where a strong slope in topography occurs).

6. THE KÖFLACH CASE STUDY: PARALLELS WITH EGS PLAYS IN EASTERN AUSTRALIAN BASINS

Whilst the Köflach area of eastern Austria is traditionally known for its coal and not for EGS energy exploration, the existence of thermally insulating lignite beds lends itself as a possible analogue for Enhanced Geothermal System (EGS) plays which typically require the existence of a shallow insulating horizon to setup a scenario of anomalously high heat occurrence, at accessibly shallow depths.

EGS exploration is now being carried out in Australia by a large number of companies, not only in inland basin settings (eg., Cooper Basin), but also in basins throughout eastern Australia where extensive coal seams are common. Our work will have implications for EGS plays in both settings.

Our 3D model of the Köflach area (when finalized) will portray diverse geology including crystalline basement, overlain by weakly metamorphosed units of the Graz Paleozoic and in turn overlain by Neogene sediments of the Styrian Basin, including coal seams.

This geologic package will ensure strong thermal conductivity contrasts in an area of high topographic relief and will therefore be a challenging case study for the geothermal module in 3D GeoModeller. Using this example we will demonstrate realistic 3D temperature and heat flow predictions verified against measured insitu-temperatures and heat flow data – at all times obeying topographic effects.

7. CONCLUSIONS

1. Plausible 3D temperature, heat flow and thermal gradient modeling results have been achieved in our test-bed case of the synthetic geology model.

2. The strong topographic relief of the synthetic model has had a dominating effect on temperature distribution.

3. Thermal conductivity contrasts have had a lesser impact on heat distribution than topography, but this is probably because scenario testing of the latter parameter was taken to an extreme.

4. Increased heating of the section at and below the capping unit occurred, as expected, due to the low thermal conductivity assigned to this unit in combination with higher thermal conductivities in the unit below (hence establishing a thermally insulating layer).

5. Generally, vertical heat flow values for the synthetic model are <0.040 Wm^{-2}. However, very high values of modelled heat flow occur where extreme topography has played a part in juxtaposing very high temperature rocks near-surface in a deeply incised valley location.

6. Generally, vertical temperature gradients for the synthetic model are <20°Ckm^{-1}, while total horizontal temperature gradients are <15°Ckm^{-1}. Much higher values of both occur: a) in the shallow sub-surface when increased heating at and below the capping unit has occurred, and b) where extreme topography has caused juxtaposition of high temperature rocks near-surface in a deeply incised valley (locations where a strong slope in topography occurs).

7. Having satisfied test-bed thermal modeling of the synthetic geology model, GeoModeller will now be applied to thermal modeling of the Köflach area, Eastern Austria – which similarly features high relief terrain and strong thermal conductivity contrasts.

8. The thermally insulating lignite beds of the Köflach area are likely to be a good analogue for Enhanced Geothermal System (EGS) plays which typically require the existence of a shallow insulating horizon to setup a scenario of anomalously high heat occurrence, at accessibly shallow depths.

9. EGS exploration in Australia is likely to benefit from this work, because practical aspects of thermal modeling demonstrated here can be replicated in any exploration programme and hence the risk of exploring for heat can be reduced at the pre-deep drilling stage.

FOOTNOTE

[1]*3D GeoModeller* is a commercial software product developed by BRGM and Intrepid Geophysics. For further information visit: www.geomodeller.com

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