Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

3D Geological Modeling of Potential Geothermal Energy Reservoirs in the Flinders Ranges, Australia

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Keywords: South Australian Heat Flow Anomaly, 3D modelling, thermal modelling, potential field data

ABSTRACT

The Flinders Ranges in Australia are located within the well defined South Australian Heat Flow Anomaly. Anomalously high heat flow is recorded in this area, offering world-class opportunities for the development of significant and economically viable Enhanced Geothermal Systems (EGS). Here, we show how a combination of potential field data interpretation and modelling with surface and sub-surface geological constraints in addition to finite element thermal models, enable us to to best delineate potential geothermal reserves. This study could be used as a benchmark for any EGS exploration in the world.

1. INTRODUCTION

Exploring for significant geothermal power generation targets requires the delineation of areas with favourable geological and thermal conditions. The hunt for such prospective areas can be further complicated in the case of Enhanced/Engineered Geothermal Systems (EGS). In Australia, prospective areas for the development of EGS have sparse data coverage and limited geological understanding. Hence, one of the priorities of the developing geothermal community in Australia is to develop reliable exploration techniques that reduce the risk and maximize the chance of success of a prospect. In this paper, we present an integrated workflow which enables a better determination of the potential of a geothermal prospect. We use the Central Flinders in South Australia, where high surface heat flows are reported, to develop and test this methodology, based on the interpretation and modelling of geophysical datasets freely available through Primary Industries and Resources South Australia (PIRSA).

2. GEOLOGICAL CONTEXT

The Flinders Ranges are located in South Australia (Fig. 1), and correspond to the inverted Late Neoproterozoic Adelaide basin. The southeastern part of the basin complex lies adjacent to an evolving passive margin related to the break-up of the supercontinent Rodinia, while intracratonic branches extend northwestward into the Australian continent (Preiss, 2000). The rocks forming the basement of the basin, exposed in various localities across the Flinders Ranges, are characterized by an anomalously high concentration of heat production element (uranium, thorium and potassium), interpreted as being the cause of elevated geothermal gradients and high surface heat flow throughout the basin (Fig. 1; e.g., Neumann et al., 2000). The total thickness of Neoproterozoic to Early Cambrian sediments deposited during the basin's history is greater than 15 km in the deepest part of the Adelaide basin (Sandiford et al., 1998). The Cambro-Ordovician Delamerian Orogeny is the main compressional event which has affected the area, and is responsible for the main period of basin inversion. However, Neogene horizontal tectonic stresses are responsible for the formation of the present-day topography (Sandiford 2003; Hillis et al., 2008). The margin of the Adelaide basin, namely the Torrens Hinge zone, Stuart shelf and Frome Embayment, present an ideal geological setting to offer world class geothermal prospects, with a "hot" basement blanketed by up to 5 kilometres of undeformed to gently deformed sediments.

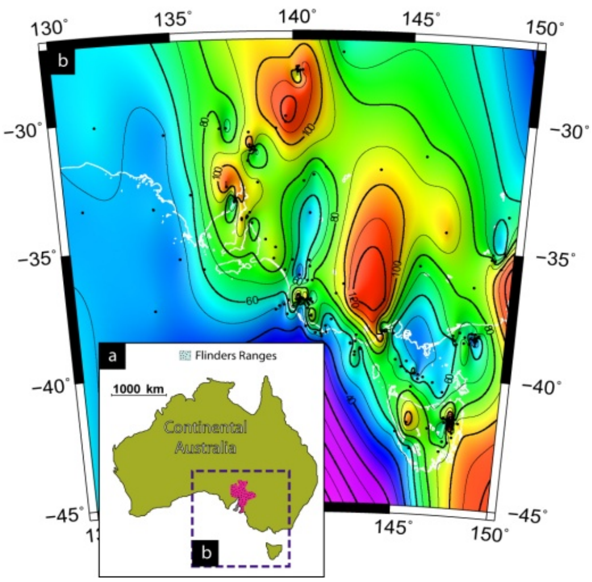

Figure 1: A/ Location of the Flinders Ranges in Australia; B/ South Australian Heat Flow Anomaly

We focused our study in the Central Flinders area, located in the central part of the Flinders Ranges. There, the basin is bounded by two cratonic nuclei, the Gawler craton to the west and the Curnamona Province to the east. The whole of the basement rocks below the Flinders Ranges are thought to be enriched in heat production elements, a hypothesis which seems more and more valid as more heat flow data across the orogen is being released. High heat flow values have been determined in both side of the basin leading to the exploration for geothermal reservoirs in this area. Therefore, a detailed model of the basement geometry below the Flinders Ranges can pave the way for the development of economically viable geothermal reservoirs.

3. DATA AND METHOD

Our methodology is based on the joint interpretation and modelling of different datasets (Fig. 2).

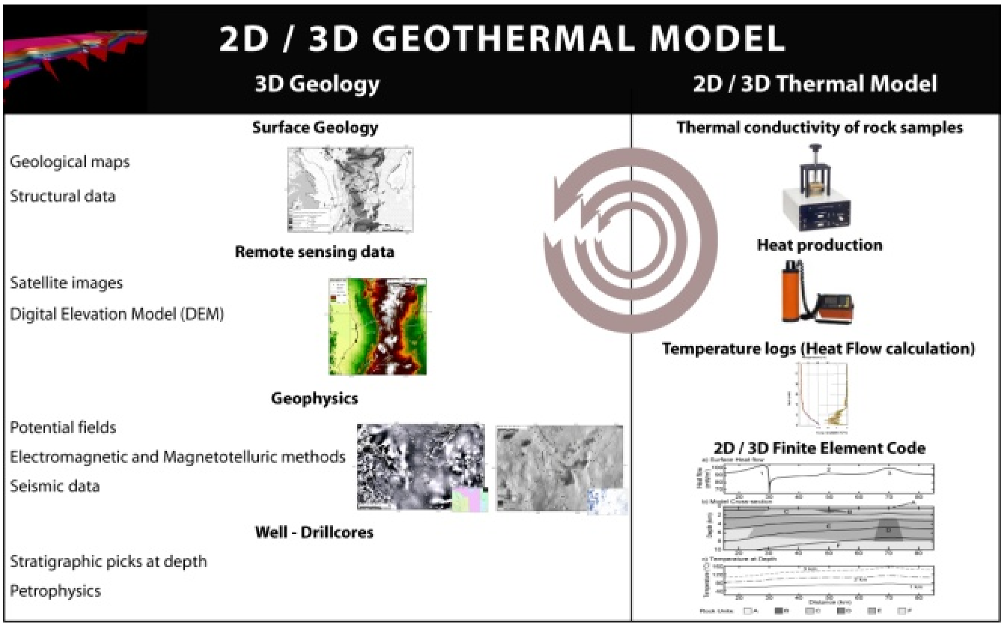

Figure 2: Methodology and data necessary for building a 3D geothermal model

Our methodology is based on the interpretation of different geological datasets, such as geological maps, structural information collected in the field. These interpretations are confronted to the analysis of geophysical data. More constraints to the model are provided by various exploration geophysics techniques. For the purpose of this study, we were able to use some seismic reflexion data acquired in the seventies across the western and eastern foothills of the Central Flinders, and more importantly a large dataset of potential field data: Bouguer anomaly and total magnetic datasets. Here is an overview of the different data used in this study:

3.1 Surface Geology Data (Fig. 3)

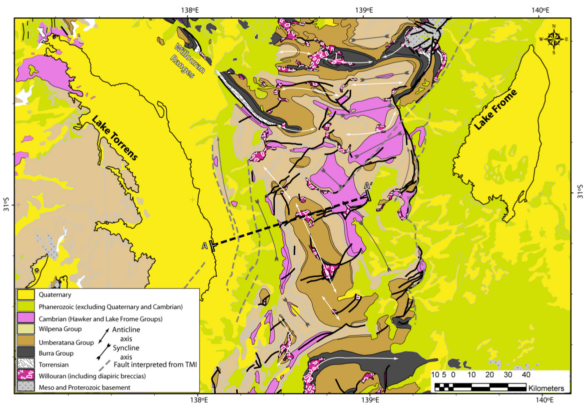

Figure 3: Geological map of the Central Flinders

Our analysis combines the use of surface data, mostly remote sensing imagery (satellite images, digital elevation model and aerial photographs), field observations (bedding, microstructural information) and the published 1:250000 geological map (Preiss, 1999).

3.2 PIRSA Bouguer Anomaly database (Fig. 4)

The Bouguer anomaly map is derived from a composite grid that merges data from numerous surveys carried out in the past 50 years. The final grid cell size is ~500m, but the original gravity stations coverage is variable. As a consequence, some sectors in the Flinders Ranges are characterized by distances between stations of up to 10kms.

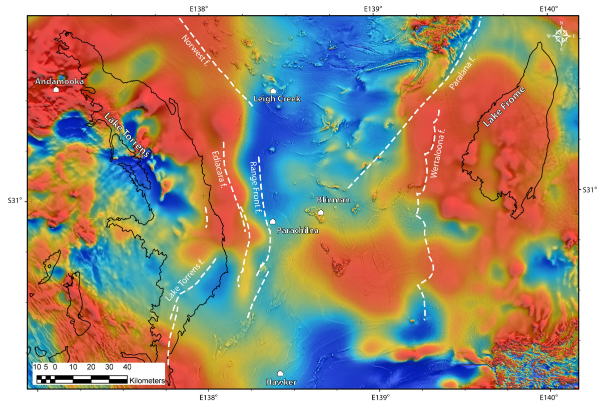

Figure 4: Bouguer Anomaly map of the Central Flinders

3.3 PIRSA Total Magnetic Intensity database (Fig. 5)

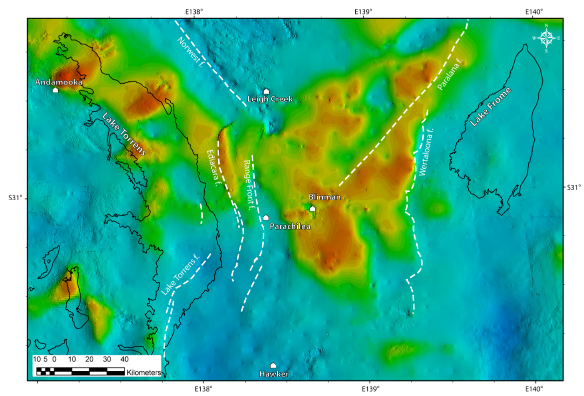

Figure 5: Total Magnetic image of the Central Flinders

The TMI image is also a composite grid compiled from a variety of surveys with different characteristics. The TMI data is characterized by flight line spacing of between 100 and 400 m, and a drape flying height of 80 m above the ground surface. The final grid cell size is 80 m, meaning that structures or marker units with across-strike length-scales of ~160 m or less are not resolvable. The data has been subjected to standard pre-gridding processing and levelling techniques.

3.4 Seismic Data

We used all the available seismic data to better constrain the geometry of the structures at depth. However, as no well has been drilled deep enough to cut through the entire sedimentary column in the vicinity of the seismic line, the interpretation of the different sedimentary package may be subject to discussion.

3.5 Petrophysical Data

In order to best constrain the forward models of the potential fields, we measured the specific gravity and magnetic susceptibility of 500 samples taken from drill-cores collected in the Torrens Hinge Zone and the Central Flinders Ranges area.

Using these datasets, we built a series of interpretative geological cross-sections (Fig. 6). These sections were exported into a commercial package, GM-SYS, and used as template for the forward modelling of the potential field data. The sections were divided into polygons, which in turn were assigned representative rock properties values (here, bulk average magnetic susceptibilities and specific gravity), derived from measurements made independently along stratigraphic drill cores. Each polygon is characterized by a single density and magnetic susceptibility, and is modelled as polyhedra with limited strike extents outside the section plane. The magnetic and gravity responses of each polygon are computed according to an analytic solution (Talwani et al., 1959; Talwani and Hiltzer, 1964) using GMSYS. Forward modelling of this type, although time consuming, allows structural models to be constrained when combined with geological and other geophysical methods. We then compared the calculated potential fields responses to the TMI and Bouguer anomaly data extracted along the cross-sections from the PIRSA dataset. Thus, to reduce the difference between the observed and calculated potential fields, we would either alter the section geometry or modify the petrophysical properties of the polygons. In this study, we strictly honoured the constraints provided by the outcropping geology and the measured rock properties. The new modelled response was then compared with the original data, and so forth until an acceptable solution was attained. The root mean squared (RMS) difference between the modelled and the calculated fields was used as an estimator of goodness of fit, as it reflects the signal to noise characteristics of the observed field data (Direen ,1998).

For the purpose of this study, we divided the sedimentary cover into 5 units, with different petrophysical properties. The basement is another unit in our model, with a constant density for all sections, but with different magnetic susceptibilities for each fault block.

This study follows a series of assumptions, all justified by independent studies. The major assumption is to consider that the densities of the rocks composing the basement units can be averaged to one single common value along the different cross-sections. Only the magnetic susceptibility is variable between the different basement blocks. This assumption offers the possibility to model the sections only in terms of crustal geometry and depth to basement (Fig. 7), without considering hypothetical and unconstrained sharp rheological contrasts within the basement rocks. In addition, we wanted to characterize the geometry of the faults at depth. We performed sensitivity analysis of the fault geometry at depth, by modifying the models varying the shear zone dips only, keeping all other parameters constant (Direen, 1998) The final sections display the geometric configuration with the minimum misfit between the observed and calculated potential fields. The final forward cross-sections are then exported to a 3D geological modelling package, Gocad, and turned into a 3D geological model of the area of study.

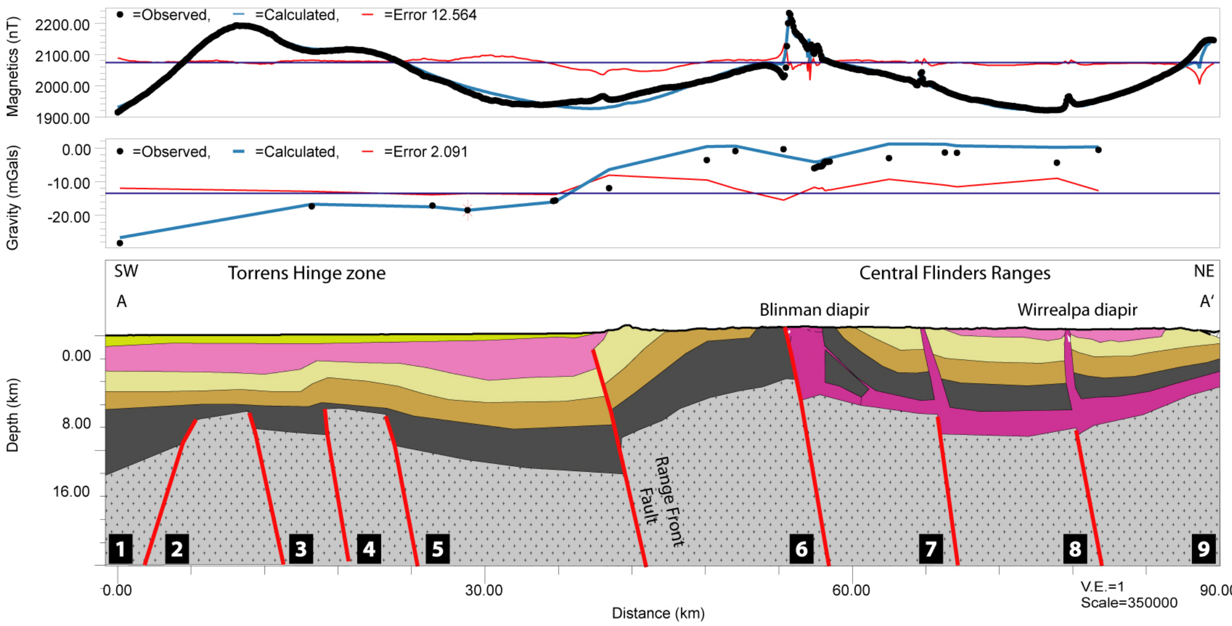

Figure 6: 2D Geological cross-section of the Central Flinders. Numbers refer to the magnetic susceptibilities used to model the basement blocks (in 10^5 SI units): 1: 0.0113; 2: 0.055; 3: 0.0176; 4: 0.033; 5: 0.029; 6: 0.027; 7: 0.031; 8: 0.031; 9: 0.046

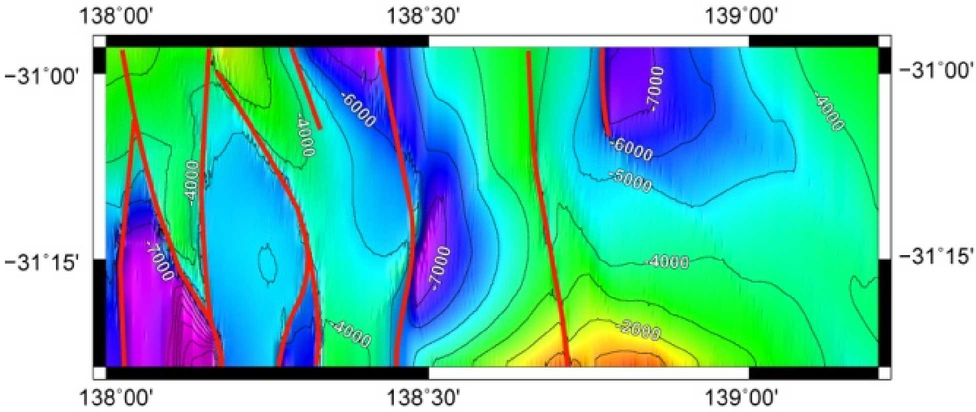

Figure 7: Depth to basement map in the Central Flinders

We also used these sections as a template for modelling the thermal state of the upper-crust in the Central Flinders (Fig. 8). A 2D finite element code was developed to thermally model the structure of a simplified geological cross-section. The cross-section represents a thick thrust bounded basin adjacent to an area with highly radiogenic basement, a model analogous to the eastern edge of the Central Flinders Ranges. The model assumes an upper boundary condition of constant temperature (25°C) and a constant basal heat flow (50mW/m^2), thermal properties for the layers are given in Table 1. The model demonstrates (from left to right):

1) the refraction of heat into a conductive basement high and the insulating effect of a thick low conductivity sedimentary basin,

2) the potential importance of intra sedimentary concentrations of radiogenic elements on the thermal structure of the basin.

3) the effect of a buried radiogenic granite.

Table 1. Thermal Properties of the Model in Figure 8.

Body	Description	Thermal Conductivity (W/m/K)	Heat Production (mW/m^3)
A	Upper Sedimentary Layer	2.0	0.0
B	High heat-producing sedimentary unit	2.4	8.0
C	Lower Sedimentary Unit	2.5	0.0
D	High heat producing granite	3.5	12.0
E	Radiogenic Upper Crust	3.0	8.0
F	Non-radiogenic lower crust	3.0	0.0

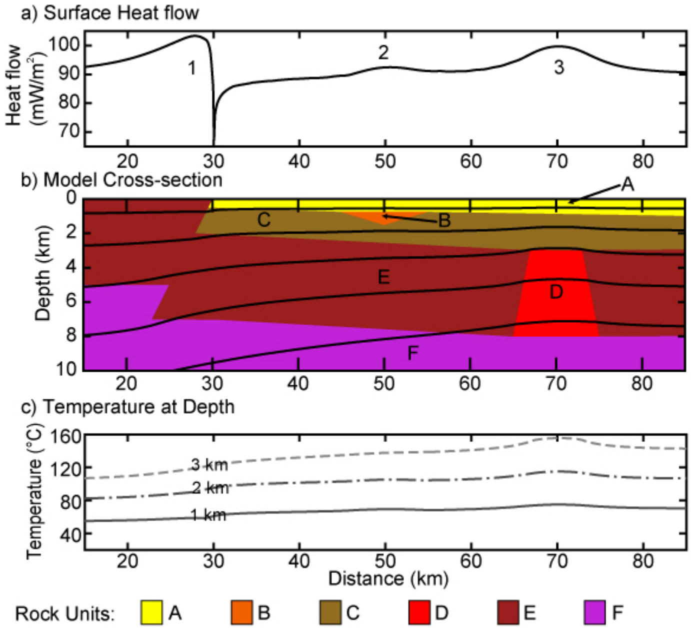

Figure 8: Simple 2D finite element thermal model from a true geological model. a) Surface heat-flow from the model. Numbers indicate the heat flow anomalies referenced in the text. b) Model cross-section: black lines are 50°C temperature contours. c) Temperature profiles at constant depth across the model

4. RESULTS

Our work reveals the structure of the Central Flinders at depth. In particular, we were able to describe the geometry and depth to the basement, a key to successful exploration strategies in this area where such information was not previously available.

We achieved the best fit between observed and calculated potential fields by modelling the geology at depth in the Central Flinders as a series of fault-bounded blocks, separating basement highs and depressions, filled by early-rift sediments (Willouran and Torrensian sequences). This shows that the early stages of the basin history were characterized by a period of opening of grabens and horsts structures, immediately filled with silico-clastic sediments. Later, the regional sag of the basin has been recorded through the deposition of thick deep water sediments, blanketing the basement topography.

5. IMPLICATIONS FOR GEOTHERMAL

Thermal modelling along with the initial geological modelling enabled us to confirm the geothermal potential of the Central Flinders Ranges. In particular, we better delineate potential targets within the basement; and identify a secondary heat target within lower Adelaidean sedimentary units (Burra Group), located within the basement depressions. Our result confirms the potential of the Flinders Ranges as highly geothermally prospective for energy generation. A temperature log obtained from shallow drilling, confirms that heat flow is anomalously high, and as a consequence, temperatures at depth are higher than in a normal continental crust. Our simple thermal models show that enough heat is stored at reasonable depth in the Flinders Ranges, to provide significant geothermal reservoirs.

CONCLUSION

Our study shows that combined three dimensional geomodelling along with thermal models makes it possible to delineate more precisely zones of high temperature in the crust. The location of a geothermal prospect is therefore facilitated, and can be refined while new data, either in terms of geology or thermal state of the crust, are recorded. This method can be applied even when little data is available, and used to help to make an informed decision whether the conditions are right for the development of geothermal HDR prospects.

ACKNOWLEDGMENTS

The authors wish to acknowledge the financial and scientific support from Torrens Energy ltd and Chris Matthews. This work also greatly benefited from thorough discussions and advices from Dr Wolfgang Preiss. We also thank the generous sponsorship from Primary Resources and Exploration South Australia and the Australian Geothermal Energy Group (Tied project 4.4).

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