Temperature interpretation and modelling for geothermal applications: GeoTemp


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One of the fundamental parameters controlling the viability of any geothermal project is the temperature of the reservoir. At the early exploration stage, it is unlikely that accurate temperature data will be available. To estimate it, engineers rely mainly on temperature data such as wireline temperature logs, drill stem tests, repeated formation tests and bottom hole temperatures, usually arising from geographically sparse measurements, often from shallow depths or having low reliability. The reservoir temperature distribution is intrinsically related to the thermal characteristics of the rock and the local fluid flow. Different thermal regimes such as conduction, advection and conduction with heat production could take place, depending on the local geology and hydrogeology. This work defines an integrated data analysis workflow for temperature interpretation, modelling and estimation based on the interpretation of geophysical wireline logs, core sample measurements, geology and hydrogeology. This workflow is packaged into the software GeoTemp.

Keywords: Temperature, thermal characterisation, interpretation, modelling, predictions, thermal conductivity, heat flow.

Motivations

Exploration for geothermal energy resources aims to locate and evaluate potential geothermal reservoirs in economically viable locations. To proceed to a thermal characterisation for temperature prediction at depth, we rely on existing thermal related data. The existing temperature data sources include bottom hole temperature, drill stem test and repeated formation test temperature and wireline temperature logs. The first sources are generally geographically and vertically sparse (often only a few data points for the whole depth of a well) and of low reliability (usually gathered through petroleum exploration rather than geothermal characterisation). Wireline temperature logs are extremely rare for deep wells (e.g. petroleum wells) but fortunately are more common for shallow wells (water monitoring and mining bores). An extensive temperature logging

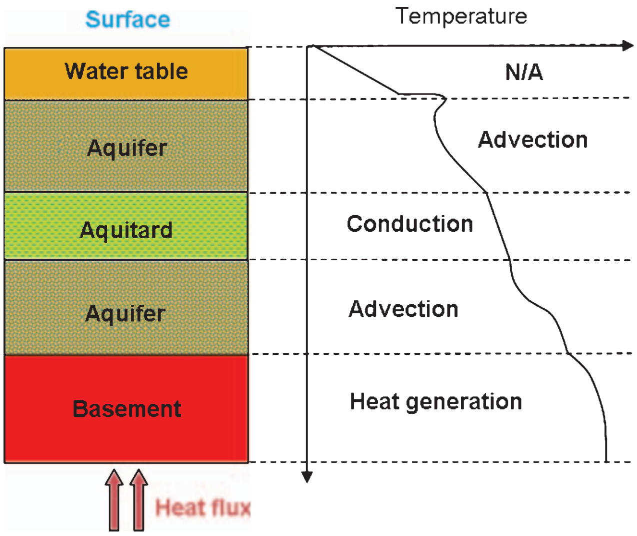

Fig. 1. *Thermal regime and temperature by formation.*

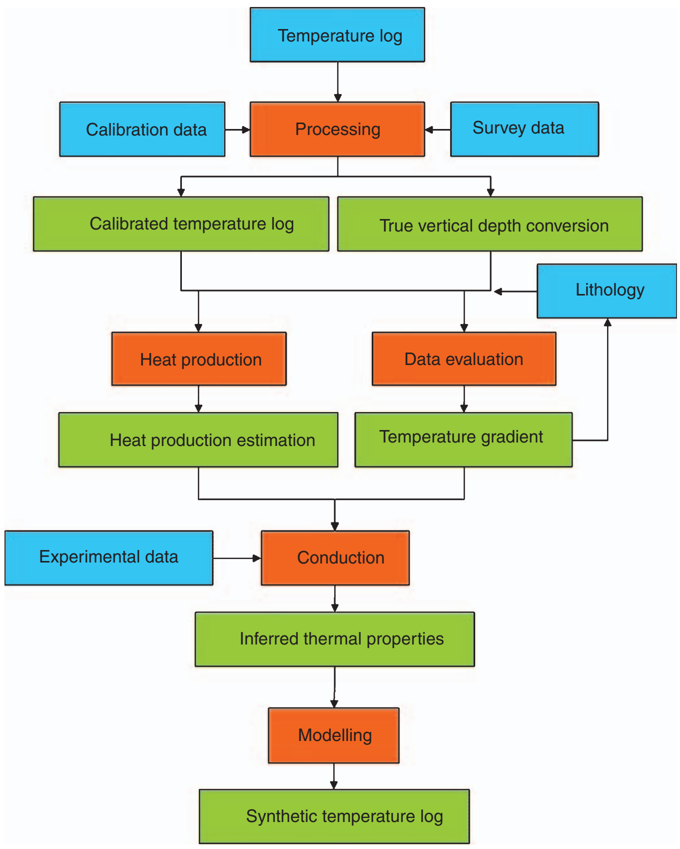

Fig. 2. *GeoTemp framework for thermal reservoir characterisation. Blue boxes represent input data, orange boxes represent the modules and green boxes represent output data.*

campaign is currently being undertaken in Australia by Geoscience Australia (Kirkby *et al.*, 2011). PressureDB provides a database of temperature data from petroleum wells (PressurePlot, 2007). Thermal conductivity data are rare. By early March 2011, for Western Australia, only 36 measurements of thermal conductivity were publicly available for the Perth Basin (HDRPL, 2008) and 50 measurements for the Canning Basin (HDRPL, 2009). These measurements were done on cores from petroleum wells situated in several Western Australian basins.

Heat is transported inside rocks by a combination of processes such as conduction, advection and radiation, defining the thermal regime. At a first approximation, for mildly heterogeneous formations, the thermal regime can be assumed to be constant. Therefore, thermal characterisation of a stratigraphic sequence could be achieved by assessing thermal regimes for each formation. Figure 1 presents a schematic of hydrogeological stratigraphy with associated thermal regimes.

To proceed towards temperature prediction at depth, quality control of the available data is required prior to any interpretation or modelling.

In this work, we present a software workflow for the processing, quality control, interpretation and modelling of temperature data and the quantitative extrapolation and interpolations of temperatures for geothermal reservoir engineering purposes. The software tool used, GeoTemp, accepts standard input files and exports pictures in common formats for reporting.

General framework

GeoTemp aims to set a protocol for inferring underground temperature and estimating rock thermal parameters based on the analysis, interpretation and modelling of temperature logs. It comprises six components corresponding to the six different stages of the process: Processing, Data viewing, Data evaluation, Heat Production, Conduction and Modelling.

Each module is independent of the other, however they are linked by an integrated framework that facilitates the workflow from processing to interpretation and then to modelling with prediction. The modules accept widely used file formats and well defined input/output files (Ricard and Chanu, 2011). For example, the LAS file format is used for wireline temperature logs. This format was defined by the Canadian Well Logging Society (http://www.cwls.org/las_info.php).

Figure 2 shows the GeoTemp workflow for temperature logs analysis.

Each module incorporates straightforward procedures for loading and interpreting the data with visualisation of intermediate and final results which may be exported for reporting purposes.

GeoTemp modules

Processing

GeoTemp Processing handles calibration of the temperature data, depth conversion from Measured Depth (MD) to True Vertical Depth (TVD) and quality control of the gamma-ray and local temperature gradient.

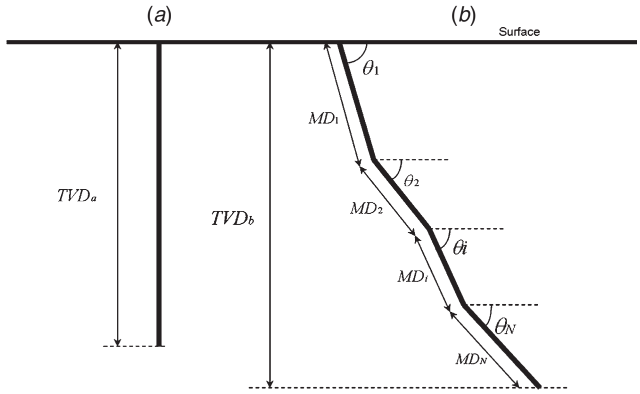

Fig. 3. *Measured Depth and True Vertical Depth for (a) a vertical well and (b) a deviated well.*

Every temperature probe has a natural drift over time, so regular temperature calibrations need to be performed and temperature data must to be corrected for drift. The GeoTemp Processing module gives the user the ability to calibrate the temperature data using a set of calibration data.

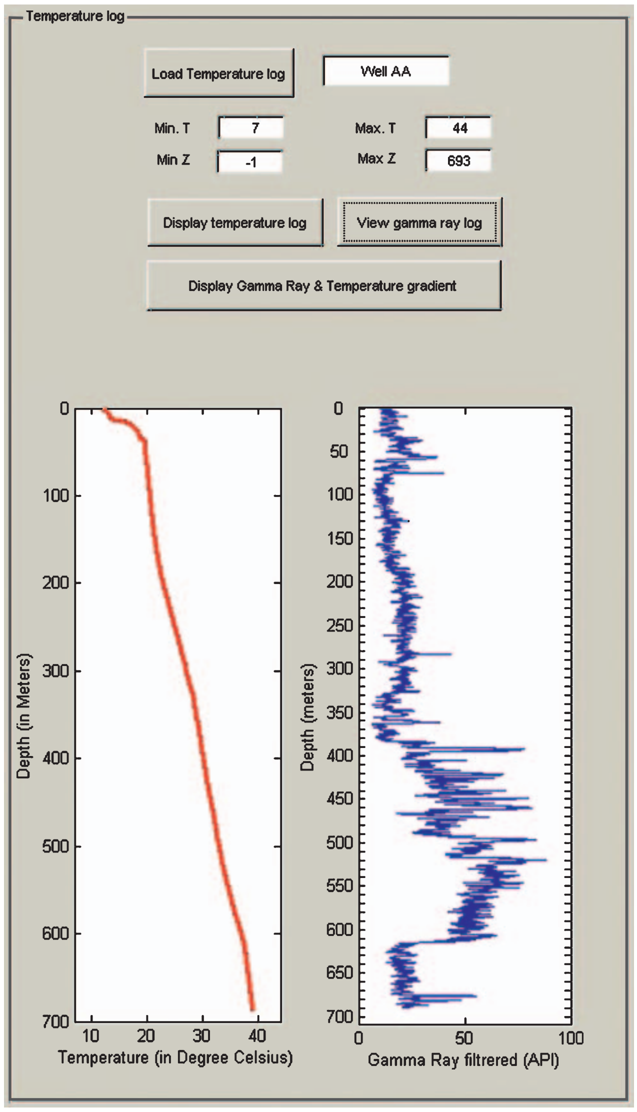

Fig. 4. *Temperature log frame screenshot.*

A second functionality of GeoTemp Processing is the ability to correct the depth from Measured Depth (MD) to True Vertical Depth (TVD) by loading temperature log (.LAS file) and survey data (.XLS file) in the True Vertical Depth Calculations frame (see Figure 3). As wells are not often strictly vertical but the temperature analysis is performed, as a standard, in true vertical depth, a conversion from Measured Depth (MD) to True Vertical Depth (TVD) is required. Using survey data, GeoTemp Processing allows the user to convert the depth from MD to TVD (see Figure 3).

The link between Measured Depth and True Vertical Depth is expressed as follows:

$$\mathrm{TVD} = \sum_{i=1}^{N} \mathrm{MD}_i \sin(\theta_i) \qquad (1)$$

where TVD is the True Vertical Depth in metres, and for each deviated segement i, MD_i is the Measured Depth in metres and θ_i is the angle in degrees.

A third functionality of GeoTemp Processing is the quality control of gamma ray and local temperature gradient data (see Figure 4) and the ability to display these for reports. These features allow the user to inspect the temperature and gamma-ray data in detail.

Viewer

GeoTemp Viewer allows the user to load and display several temperature logs at once (see Figure 5). By plotting several temperature logs at once, the user can easily compare the temperature logs.

Evaluation

The third component provides the tools to perform quality control of the temperature data, check the consistency of the temperature, lithology and gamma ray data, evaluate thermal regimes by formation, and finally calculate the temperature gradients by formation (see Figure 6). This module is designed to interpret thermal profiles with respect to a vertical conduction model.

It allows the viewing of the temperature and gamma-ray data by formation and therefore checks the consistency between formation tops and gamma-ray markers. If inconsistency is noted, formation tops can be adjusted. Once formation tops and gamma-rays are consistent, linear temperature gradients can be calculated by formation. In the case of vertical heat conduction with no heat production, the temperature profile obeys:

$$T(z) = T_0 + q_0 \sum_{i=1}^{N} (\Delta z_i / \lambda_i) \qquad (2)$$

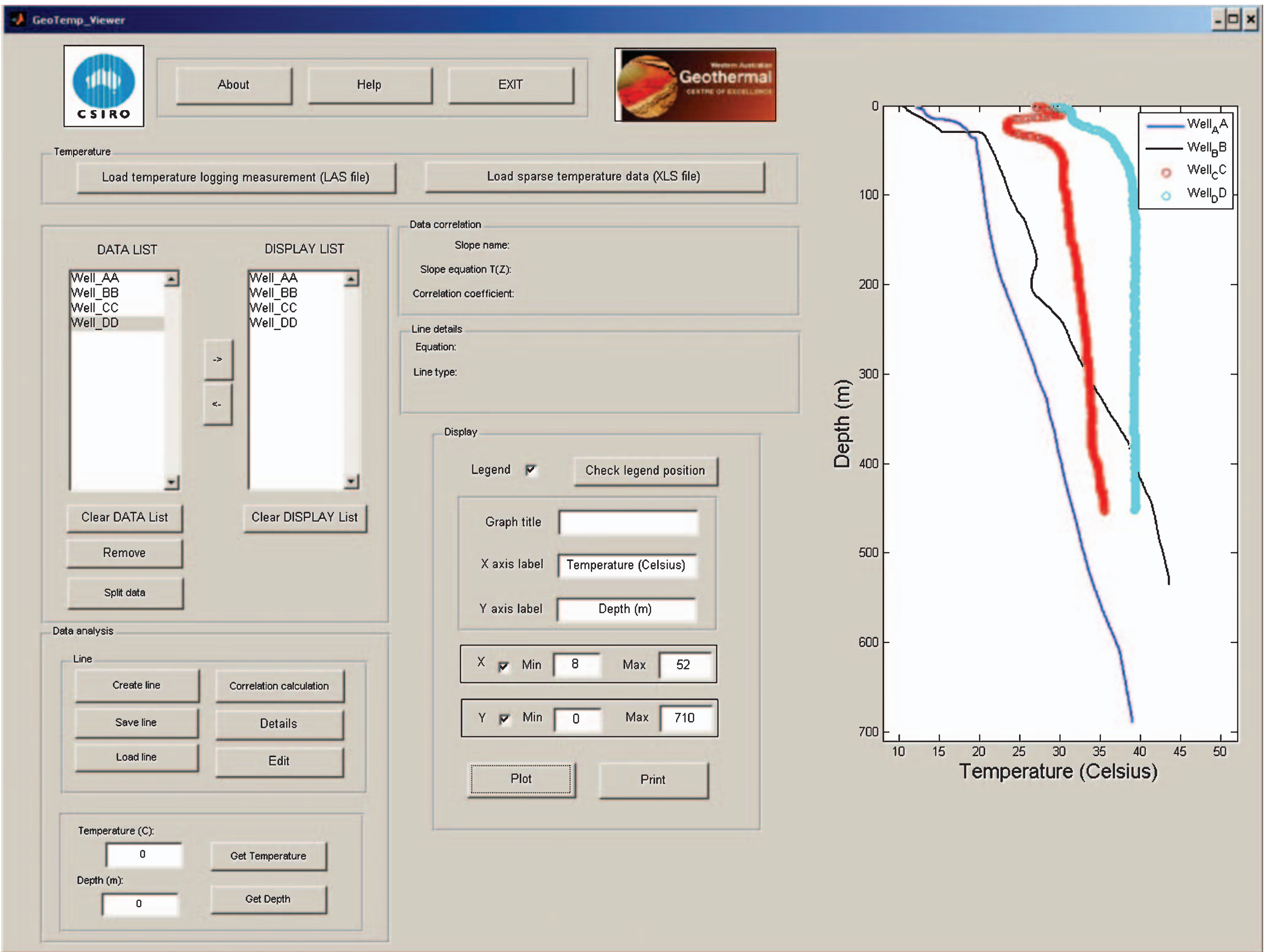

Fig. 5. *Viewer module screenshot.*

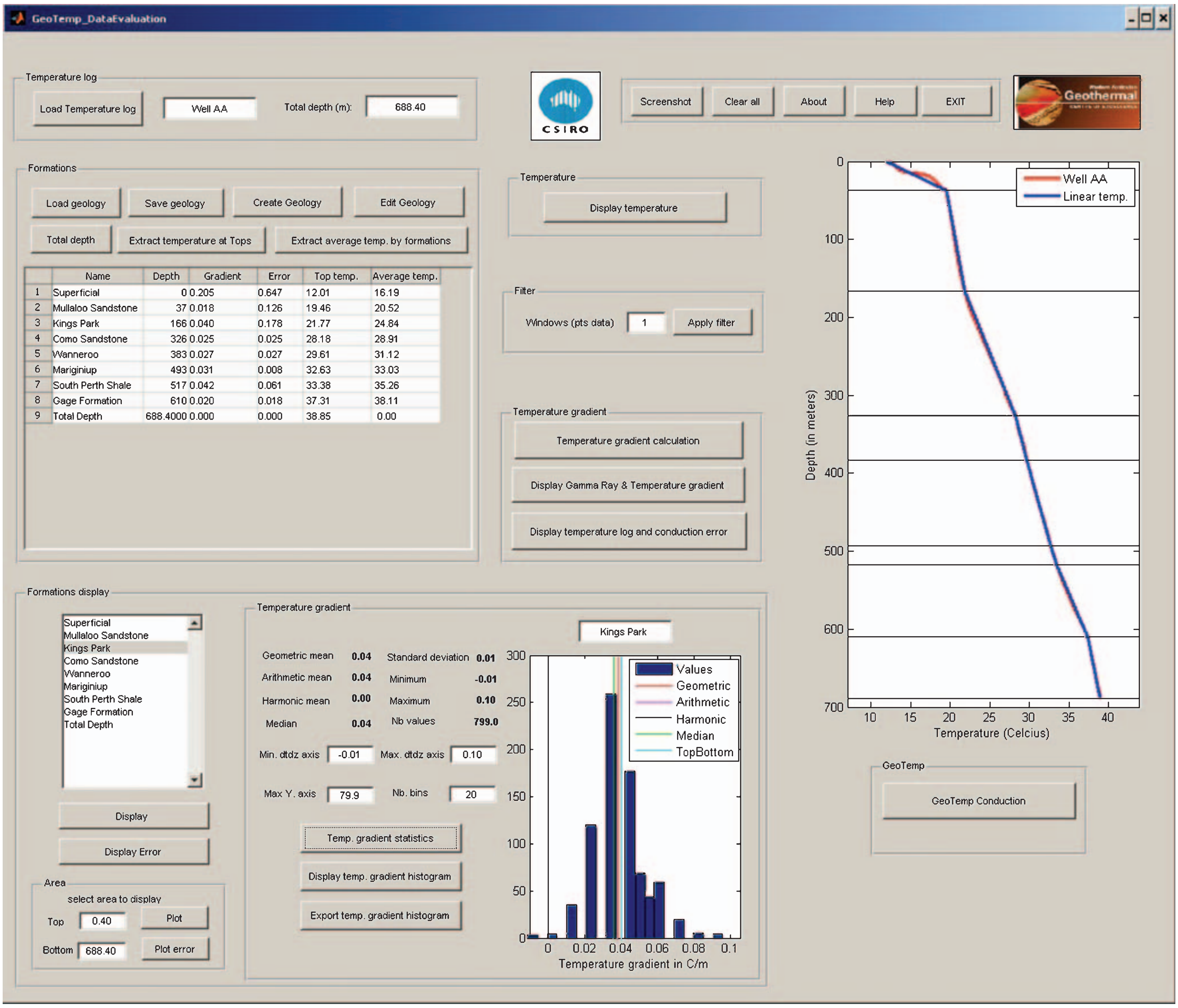

Fig. 6. *Data evaluation module screenshot.*

where T is temperature, T_0 is surface temperature or another reference temperature, q_0 is the constant heat flow density, z is depth below ground level and λ_i is thermal conductivity in the depth interval Δz_i (Kutasov, 1999).

For each formation, a normalised quadratic error between the linear temperature gradient and the real temperature data is calculated to quantify the suitability of the conductive thermal regime assumption. If the quadratic error is relatively small, to be determined by the user, then the vertical conduction assumption is accepted.

Heat production

The rate of radiogenic heat generation within rocks is related to the quantity of radioactive material present, the rate of decay and the energy of the emitted particles. Gamma-ray spectrometers provide the most direct method for measuring the abundance of uranium, potassium and thorium in rock (Beardsmore and Cull, 2001). The estimation of heat production rate by formations (Figure 7) is done from the gamma-ray wireline log using the empirical equation:

$$A = 0.0158(\mathrm{GR} - 0.8) \qquad (3)$$

where A is the heat generation count in μWm^{-3} and GR is the gamma ray count in API units.

Conduction

Assuming a vertical conduction regime, a conductive interpretation of temperature logs can be performed using GeoTemp Conduction (Figure 8). In this module, the temperature gradient combined with experimental thermal conductivity measurements can be used to calculate the vertical heat flow and double-check the consistency of thermal conductivity, vertical heat flow and temperature gradient.

Modelling

The sixth component focuses on conductive modelling and temperature prediction at target reservoir depth (Figure 9).

Interpreted parameters such as thermal conductivities by formation, vertical heat flow and temperature at a given depth are used to calculate a synthetic temperature log.

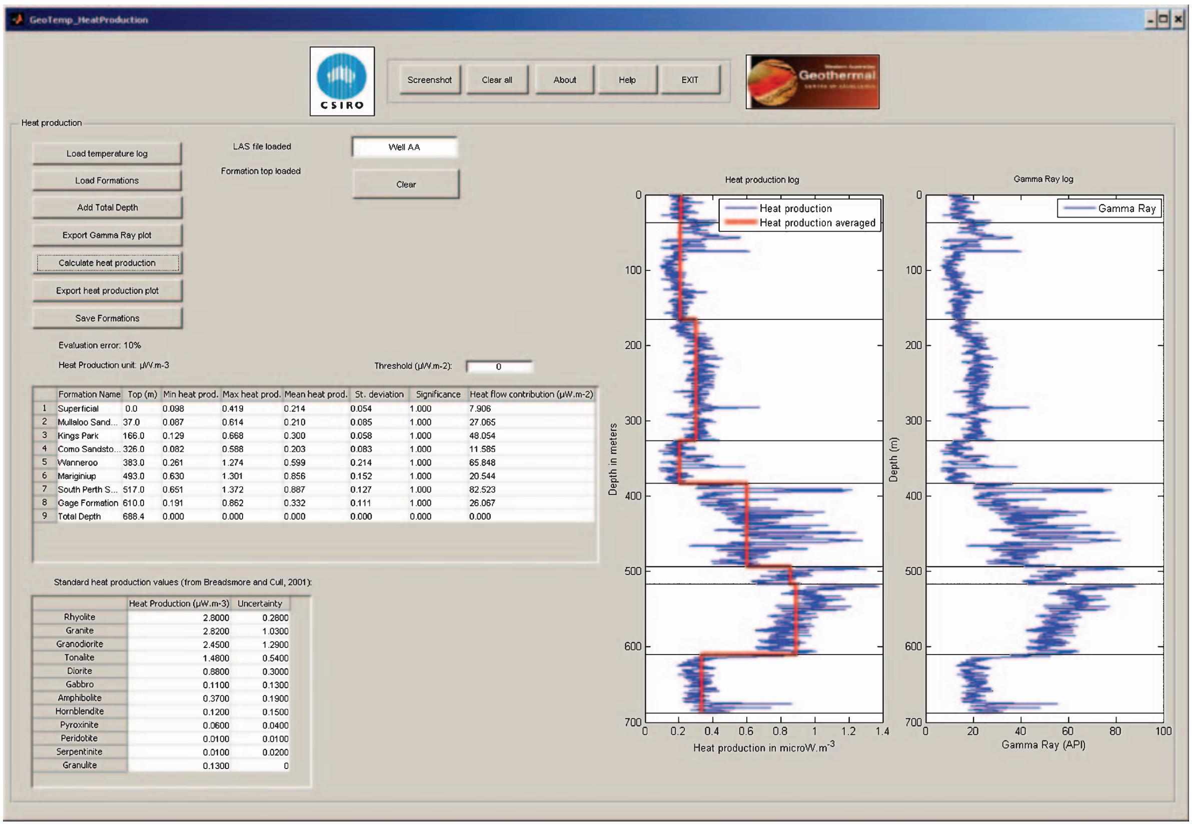

Fig. 7. *Heat production module screenshot.*

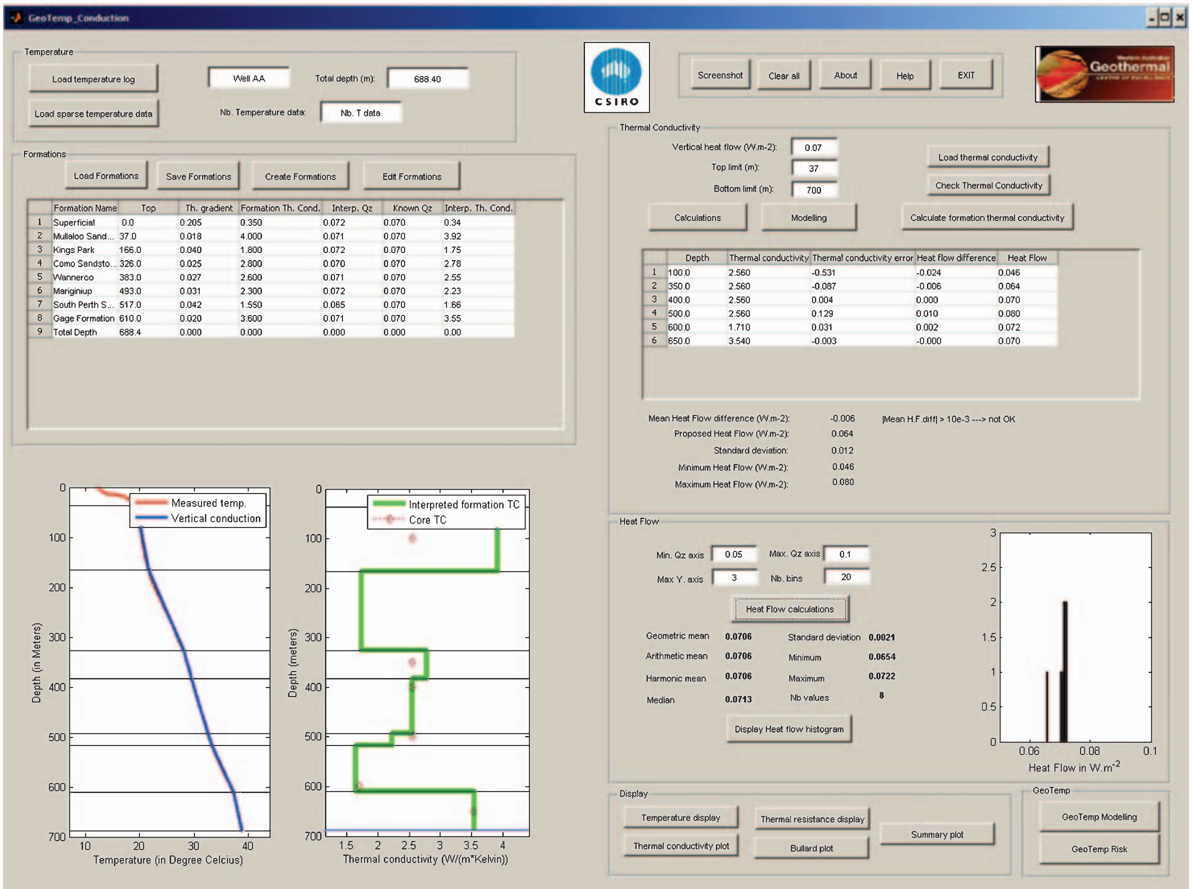

Fig. 8. *Conduction module screenshot.*

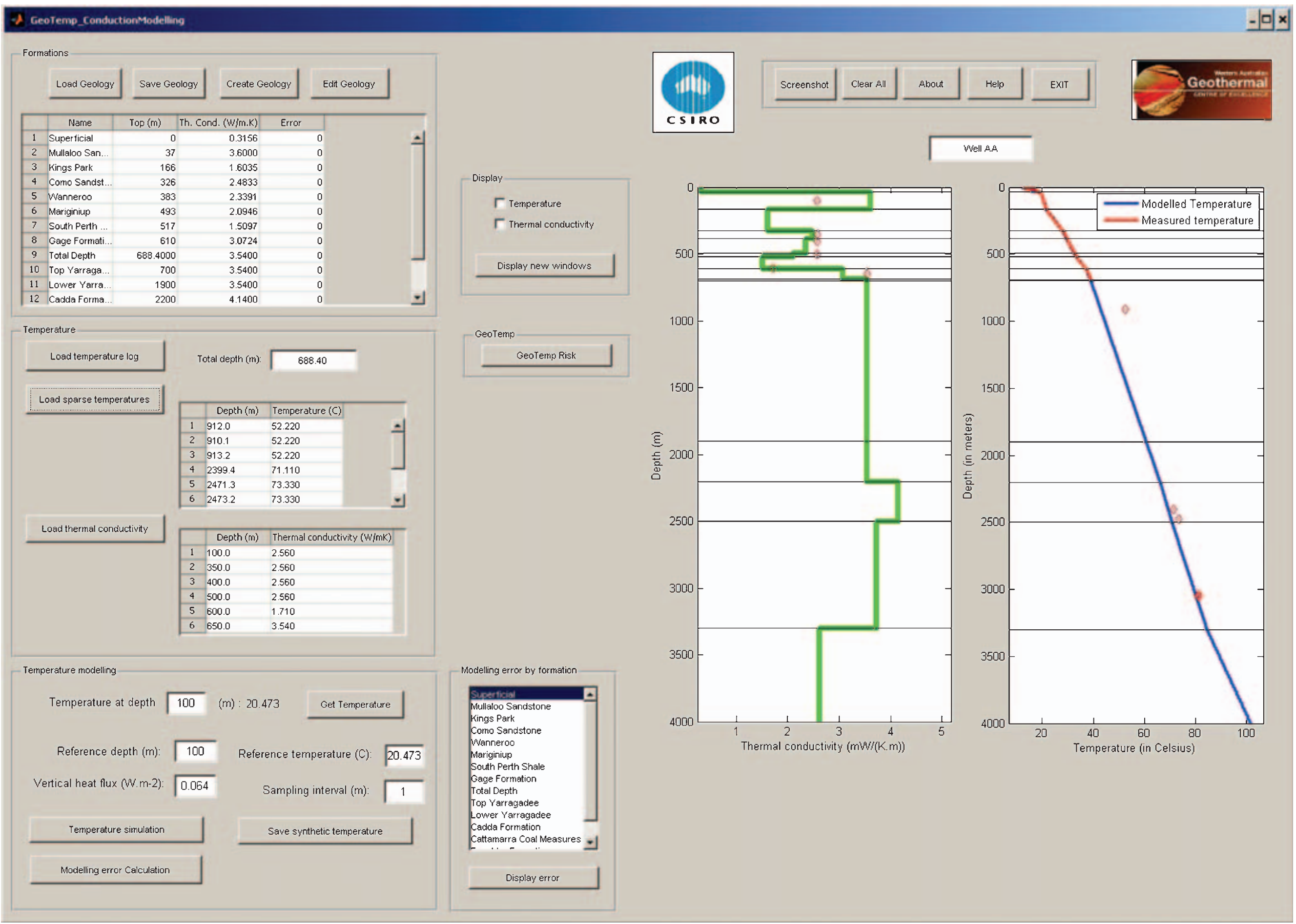

Fig. 9. *Modelling module screenshot.*

Normalised quadratic error between the real and the synthetic temperature logs is calculated for quality evaluation of the interpretation/modelling process. Temperature predictions can be made for depths below the supporting measurement data if vertical heat conduction is assumed.

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