GeoTemp: A framework for temperature interpretation and modelling

L.P. Ricard*1,2, J-B. Chanu2, L. Esteban2

*1 Western Australian Geothermal Centre of Excellence, CSIRO, Kensington, WA 6151
2 CSIRO Earth Science and Resources Engineering, Kensington WA 6151

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 to have access to accurate temperature data. To estimate it, engineers rely mainly on temperature data such as wireline temperature logs, Drill Stem Tests, Repeated Formation Tests and Bottom Hole Temperatures which usually arise from geographically sparse measurements, often from shallow depths or have low reliability. The reservoir temperature distribution is intrinsically related to the thermal properties of the rock and formation chemistry and dynamics. Different thermal regimes such as conduction, advection and conduction with heat production could take place, depending on the local geology, structures and hydrogeology.

This work defines an integrated data analysis workflow for temperature interpretation, modelling and estimation based on the interpretation of geophysical wireline logs, sparse temperature data, core sample measurements, geology and hydrogeology. This workflow is packaged into the software GeoTemp.

Keywords: Temperature, thermal regime, logging, modelling, predictions, thermal conductivity, heat flow

1 Introduction

Exploration for geothermal energy resource aims to locate and evaluate potential geothermal reservoirs in economically viable locations. To proceed to a thermal characterization 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 gather through petroleum exploration rather than geothermal characterization). 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 campaign is currently being undertaken in Australia by Geoscience Australia (Kirkby et al., 2011) and state agencies such as the Victorian Department of Primary Industry, the Queensland and the Western Austrian Geothermal Centre of Excellence (Reid et al., 2011). PressureDB/PressurePlot (PressurePlot, 2007) and OzTemp (Holgate and Gerner, 2010) provide database of temperature data from petroleum wells. By early March 2011, for Western Australia, only 36 sample 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 in laboratory without in-situ conditions from petroleum wells spread all over the 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 characterization of a stratigraphic sequence could be achieved by assessing thermal regimes for each formation (Fig. 1).

Figure 1: Schematic of hydrogeological stratigraphy with thermal regime and temperature by formation

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

To help to reach temperature prediction with associated uncertainties, we present a workflow from the processing towards quality control, interpretation, modelling and quantitative extrapolation and finally spatially interpolations of wireline temperature logging measurement for geothermal reservoir engineering purposes. This software, GeoTemp, proposes several independent tools to manipulate the data and
proceed to some simple geographical understanding. GeoTemp accepts standard input files and exports pictures in common formats for visualization and reporting.

2 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 wireline temperature logs and core sample data.

The GeoTemp was built with three distinct components: (i) Wireline workflow, (ii) Wireline workflow support and (iii) PressurePlot analysis.

Wireline workflow is formed of 6 modules corresponding to the different steps of the process: Processing, Data evaluation, Heat Production, Conduction, Conduction Modelling and Risk.

Each module is independent from the others, however, they are linked in an integrated framework that facilitates the workflow from processing to interpretation and then to modelling with prediction (Fig. 2).

Wireline workflow support proposes four modules for data handling: Viewer, Formation Management, Guided Analysis and Regional Assessment.

PressurePlot analysis represents its own module for simple petroleum data analysis.

All the components accept widely used file formats and well defined input/output files (Ricard and Chanu, 2011). Each module incorporates automatic procedures for loading and interpreting the data with visualization of intermediate and final results which may be exported for reporting purposes.

3 GeoTemp Wireline Workflow

3.1 Processing

GeoTemp Processing handles three functionalities: 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.

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

The non-perfect verticality of wells imposes 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 TVD Calculations frame (Fig. 3). Using survey data, GeoTemp Processing allows the user to convert the depth from MD to TVD by simple orthogonal projections.

The link between Measured Depth and True Vertical Depth is expressed as follow (equation 1):

\[ TVD = \sum_{i=1}^{N} MD_i \sin(\theta_i) \]  

where \( TVD \) is the True Vertical Depth in meters, and for each deviated segment \( i \), \( MD_i \) is the Measured Depth in meters and \( \theta_i \) is the angle in degrees.

Figure 3. MD/ TVD correction: (a) vertical well MD = TVDa and (b) deviated well, MDi corrected to TVDb.
A third functionality of GeoTemp Processing is the quality control of gamma ray and local temperature gradient data (Fig. 4) and the ability to graphically display. It also provides real and filtered temperature gradient values as geometric, arithmetic and harmonic means, median, standard deviation, minimum, maximum and number of values in two separate frames. These features allow the user to inspect the temperature and gamma-ray data in detail.

Figure 4: Temperature log frame screenshot

### 3.2 Evaluation

The second module of the workflow provides the tools to perform quality control of thermal profiles with respect to a vertical conduction model, check the consistency of the temperature, lithology and gamma ray data. It also evaluates thermal regimes by formation units and finally calculates their corresponding temperature gradients (Fig. 6).

Gamma Ray (GR) can be analysed and displayed within each formation units to link the unit limits with GR markers.

If inconsistency is detected, unit limit can be adjusted. Linear temperature gradients can then be calculated by formation. In the case of vertical heat conduction with no heat production, the temperature profile obeys to (equation 2):

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

where $T$ is temperature (Celsius degree), $T_0$ is surface temperature or another reference temperature, $q_0$ is the constant heat flow density, $z$ is depth below ground level (metres) and $\lambda_i$ is thermal conductivity (W/m/K) in the depth interval $\Delta z_i$ (Kutasov, 1999).

For each formation, a normalized 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 satisfactory by the user, the vertical conduction assumption is accepted and used for the further modules.

### 3.3 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 is done from the Gamma-ray wireline log using the empirical equation (equation 3):

$$A = 0.0158(\text{GR} - 0.8)$$

where $A$ is the heat generation count in $\mu W m^{-3}$ and $\text{GR}$ is the gamma ray count in API units.

Figure 5: Data evaluation module screenshot

Figure 6: Heat production module screenshot
3.4 Conduction

Assuming a vertical conduction regime, a conductive interpretation of temperature logs can be performed using GeoTemp Conduction. 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.

![Image of Conduction module screenshot](image)

**3.5 Conduction Modelling**

The fifth component focuses on conductive modelling and temperature prediction at target reservoir depth.

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. Normalized 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.

![Image of Conduction Modelling module screenshot](image)

3.6 Risk

Uncertainties linked to the measurements, to the interpretation and to the modelling have to be taken into account in the prediction process. GeoTemp Risk allows the user to specify for a conductive system along with uncertainties on the heat flow and the thermal conductivities. Given those uncertainties, an envelope temperature log could be defined as uncertainty range on the temperature prediction. By specifying reservoir depth interval, average temperatures could be calculated.

![Image of Risk module screenshot](image)

4 GeoTemp Wireline Workflow Support

4.1 Formation Management

Geology management module enables the user to create or edit a lithology. Accesses to this module are from GeoTemp Framework but also from Geotemp Data Evaluation, Geotemp Conduction, Geotemp Modelling and Geotemp Risk. These modules are significantly different and the associated geology data inputs of these modules are varying. For each module, different parameters are needed if the user wants to create a new formation.

![Image of Formation Management module screenshot](image)
4.2 Viewer
GeoTemp Viewer allows the user to load and display several temperature logs at once (Figure 5). By plotting several temperature logs at once, the user can easily compare the temperature logs.

![Figure 11: Viewer module screenshot](image1.png)

4.3 Regional assessment
In this module, a 2D spatial distribution analysis of the temperature field is calculated using the 1D temperature logs. Extraction of temperature at depths is also possible and exportable to Microsoft Excel spreadsheet.

![Figure 12: Regional Assessment module screenshot](image2.png)

4.4 Guided Analysis
Guided analysis makes calculation of conductivity, heat flow, heat production, temperature calibration, temperature gradient and true vertical depth for several wells in a same time. It need a list of file names as an input and then do calculations and may display results on graphs and table.

![Figure 13: Guided Analysis module screenshot](image3.png)

5 GeoTemp PressurePlot
GeoTemp Pressure Plot allows the user to load and display temperature data and gives information about the data type and data reliability. This module, as the GeoTemp Viewer module, enables the user to create lines, especially envelope lines and linear regression lines of sparse temperature data.

![Figure 14: PressurePlot module screenshot](image4.png)

Acknowledgments
The Western Australian Geothermal Centre of Excellence (WAGCOE) is funded by the Western Australian government. This work has benefited from the CSIRO ESRE Petroleum Geoscience program Capability Development Fund.

The authors are grateful to Gemma Bloomfield, Guillaume Pons, Sebastian Gutbrodt, Lynn Reid and Mike Trefry for their inputs, tests or suggestions.

The authors also express their gratitude to Alison Kirky, Rikki Weber and Tim Jones from Geoscience Australia for the evaluation of the software at early stage of development.
References


