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PERMEABILITY STRUCTURE AT WAIRAKEI: INSIGHTS FROM INTERPOLATED STRATIGRAPHY AND TEMPERATURE

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SUMMARY –Drillhole temperatures and stratigraphic logs from the Wairakei Geothermal Field were interpolated using kriging. This is part of a multidisciplinary approach aimed at refining the conceptual model of Wairakei. 2D-imaging of interpolated temperature and stratigraphy is used here to discuss geological controls on fluid flow.

1. INTRODUCTION

Improving the understanding of the permeability structure of geothermal fields is critical for defining exploration targets and expansion or management strategies. Advancing our knowledge of permeability and conceptual modelling of geothermal systems requires a multidisciplinary approach. As an example, we present here interpolated stratigraphy and temperature data from the Wairakei Geothermal Field, Taupo Volcanic Zone, New Zealand. Wairakei was the first liquid-dominated geothermal system in the world to be exploited for electricity generation, with production starting during the late 1950's. Wairakei was targeted for this study because of the large cumulative database of scientific information and the long-standing effort in modelling the reservoir (Mannington et al., 2004).

2. METHODS

2.1 Data limitations

The reliability of an interpolated model depends not only on the interpolation method but also on the data reliability. Prior to interpolation, assessment of the strengths and weaknesses of each dataset was performed.

Temperature

Temperature is an objective parameter, i.e., not subject to interpretation. In spite of this, there are a number of potential uncertainties in temperature data. For instance, logged temperatures may not be necessarily representative of formation temperatures, either due to disturbances associated with drilling mud circulation and/or because the well has not warmed up to equilibrium temperatures. In the latter case, if two or more temperature measurements are logged at the same depth but at different shut-in times (although closely spaced in time – say months at the longest), then analytical corrections can be applied to measured temperatures (e.g. Horner Method; Dowdle and Cobb, 1975; Verma and Santoyo, 2006). At Wairakei, the lack of systematic measurements over time greatly hinders such analyses. Assessment of data validity was mostly based on thorough review of temperature profiles and accompanying drilling reports. Another aspect of temperature data quality is the potential for variations induced by exploitation. Quantification of these changes is not straightforward at Wairakei because early, "near natural state" and late, "disturbed" temperatures are usually not available for the same well.

Stratigraphy

Stratigraphy has the advantage that it is not subject to relevant temporal changes (on a 10^1 yr scale). However, compared with temperature, stratigraphy is a relatively subjective parameter. At Wairakei, >99% of drilling material is cuttings, usually hydrothermally altered, posing a challenge to the geologist in charge of interpretation. Wood (1994) and Wood and Browne (2000), among others, synthetised the diverse stratigraphic interpretations at Wairakei.

Stratigraphic data used here include both early geological logs as reported by Grindley (1965) and Steiner (1977) as well as logs from the most recently drilled wells. The stratigraphic nomenclature adopted here is based on Grindley's system. In some cases, however, stratigraphy has been re-interpreted or re-defined. For instance, Grindley (1965) defined 4 members within the Huka Falls Formation (HFF), namely, Hu1 to Hu4, from bottom to top. In many geological logs, Grindley (1965) was unable to make the distinction between the uppermost members Hu3 and Hu4, which was reflected in the loose definition of the member Hu3-4. In order to address this ambiguity, we adopted subdivisions used by DSIR and GNS Science since 1990 for all the Wairakei drillholes. Grindley's members Hu3 and Hu4 are grouped into a single member named *Huka Falls Formation Upper*, and members Hu1 and Hu2 are referred to as *Huka Falls Formation Lower* and *Huka Falls Formation Middle*, respectively.

From a lithological standpoint, members Hu1 and Hu3-4 are dominated by relatively impermeable, silt/sand grade lacustrine sediments (Grindley, 1965). A conspicuous exception to this pattern was a "conglomerate"-type lithology in member Hu1 from the Te Mihi area wells described by Grindley (1965) and Healy (1984), which was later re-defined as *Rautehuia Breccia* (by C. P Wood; DSIR). The origin of the Rautehuia Breccia remains unresolved, and some authors have interpreted it as a hydrothermal explosion breccia (e.g. Bogie et al., 1995).

For the oldest units logged at Wairakei, collectively referred to as *Ohakuri group* by Grindley (1965), we adopted the term *Tahorakuri Formation*, following Gravley et al. (2006). Other formation names used by Grindley (1965) like *Wairakei Breccia* and *Wairakei Ignimbrites* have been superseded by *Oruanui Formation* and *Whakamaru Ignimbrites*, respectively, based on correlation with regional units.

2.2 Interpolation algorithm

Given the uncertainties in drillhole data, it is important to use an interpolation method that allows quantification of uncertainty, such as kriging. There are a number of additional benefits in using Kriging, including:

1) kriging has a declustering property and the ability to handle screen effects. These two aspects are of paramount importance when dealing with irregularly spaced data, such as drillhole data;

2) kriging is an exact interpolator, that is, interpolations honour data values at sampling points;

3) kriging can incorporate spatial trends inherent to data. In this context, temperature tends to increase with depth.

It is worth noting here that conventional interpolation methods such as inverse-distance are not suitable for interpolation of drillhole data. Olea (1999) provides a detailed description of the kriging algorithm; only some general aspects of kriging are outlined below. Firstly, let T_o be the estimated value of the attribute T at the interpolation location $X_o = (x_o, y_o, z_o)$. T_o is estimated as:

$$T_o = \sum_{i=1}^{n} T_i \lambda_i \qquad (1)$$

where T_i is the temperature at the sampling point i, λ_i is the weighting coefficient, and n is the number of sampling points. There are infinite combinations of weights that can be chosen, each of which will give a different estimate. There is, however, only one combination that will give a minimum estimation error. It is this unique combination of weights that kriging attempts to find.

In kriging, the error is characterized by means of the variance (γ) of the attribute in question. The variance is a function of the separation distance, or lag distance (h), between two sampling points. The basic principle is that the closer two sampling points, the more similar the attribute values (i.e. the smaller the variance; $\gamma(h) = 0$ at $h = 0$). By calculating the lag distances and variances between all sampling points, a representative function of variance vs. lag distance, known as the *empirical variogram*, can be found for the data under analysis. The mathematical function that best describes the form of the empirical variogram, referred here as the *model variogram*, is used to predict the variance of the attribute at any given lag distance (Figure 1). For instance, temperature at Wairakei was found to match a spherical variogram (Figure 1), whose mathematical expression is given by:

$$\gamma(h) = C\left(\frac{3h}{2a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right) \qquad (2)$$

(Olea, 1999). Equation 2 is valid for $0<h<a$; for $h>a$, $\gamma(h)=C$. Coefficients C and a are referred to as sill (maximum variance) and range (lag distance at which variance becomes maximum and constant), respectively. In statistical terms, the range quantifies the distance at which samples become uncorrelated from each other. For temperature data from Wairakei, a = 3.5 km.

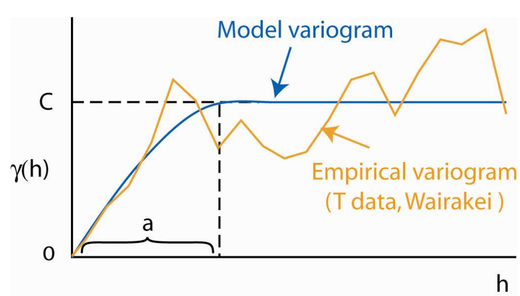

Figure 1 – Empirical and modelled variogram obtained along a N45W-trending (horizontal) direction for Wairakei temperature data.

A valid variogram is calculated along a drift-free direction (horizontal for temperature).

Comparison of several directional variograms can be used to determine spatial anisotropies of the attribute of interest. At Wairakei, the same spherical model was found to suitably describe the variation of temperature along all directions.

For *xyz* data (e.g. well data for geological surfaces), kriging is routinely available in commercial software (e.g. Surfer, ArcGIS). When dealing with one more dimension (e.g., *xyzt* data), commercial options are generally more limited. In this study, we made use of GEOINTERPOLATOR, a MATLAB code for interpolation of both *xyz* and *xyzt* data. Two varieties of kriging were implemented in GEOINTERPOLATOR: *Ordinary kriging*, for interpolation of attributes without drift (e.g. local geological units at Wairakei), and *Kriging With Trend*, for interpolation of attributes with drift (e.g. temperature). All the interpolations presented here have a spatial resolution of 30 m.

3. RESULTS AND DISCUSSION

Figure 3 shows temperature and stratigraphy for a N50E-striking cross section through our model The location of the cross section is shown in Figure 2. Some general observations that can be made from Figure 3 include:

1) Theoretically, in areas where heat transfer is dominated by conduction (low permeability), temperatures will approach those dictated by the conductive thermal gradient. In areas where heat transfer is dominated by convection (high-permeability), temperatures will approach those dictated by the boiling-depth curve (BDP). Areas with temperatures in excess of the BDP (i.e. convection-dominated, plus possible excess enthalpy associated with steam zones) occur within the Waiora Formation and to lesser extent in the HFF. The Waiora formation was been indeed identified as the main productive unit at Wairakei (Grindley, 1965; Wood, 1994), and as a whole, remains a valid drilling target.

2) Rhyolite domes and andesite flows in general do not represent thermal barriers within the geothermal field, which suggests that these are permeable units.

3) A prominent temperature inversion to the north-east closely coincides with the Whakamaru Ignimbrites-Waiora Formation contact. This suggests that in this area the Whakamaru Ignimbrites unit is relatively impermeable. However, the major upflow of the system circulates across the Whakamaru Ignimbrites, suggesting permeable paths within it.

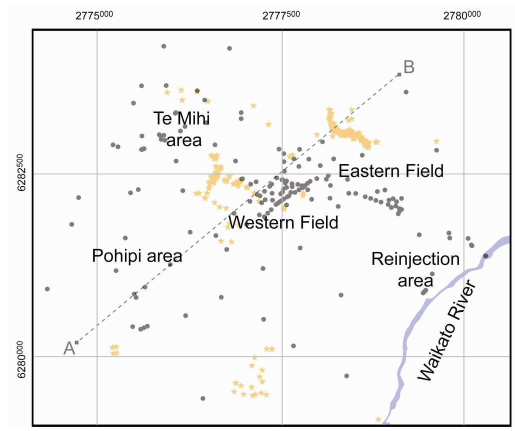

Figure 2 – Wairakei Geothermal Field in plan view showing the location of the cross section in Figure 3. Orange stars and black circles represent thermal manifestations and geothermal wells, respectively.

At this point it is convenient to point out that interpolation is only a tool to assist geological interpretations. It does not substitute for the geologist. The interpolated surfaces of this study are those that minimize the errors in the estimates. In practice, this means that discontinuities in temperature and stratigraphy associated with faults, erosional surfaces, etc. are smoothened. The cross section in Figure 3 should be regarded therefore as a guide for interpretation and the future line of work is to incorporate structural interpretations.

4. FINAL REMARKS

The objective of the present study is to illustrate the utility of combined interpolated models in refining the conceptual model of a geothermal system. Future work will focus in incorporating more datasets, such as hydrothermal alteration, geochemistry and structures.

5. ACKNOWLEDGEMENTS

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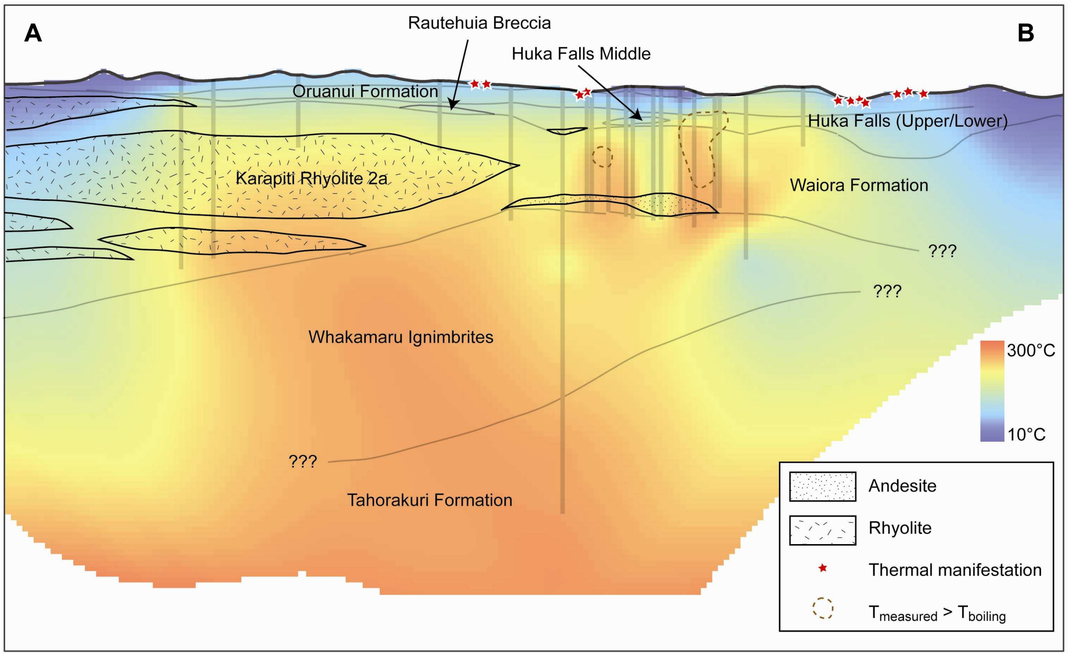

Figure 3 – Vertical cross section oriented N50E showing temperature distribution together with stratigraphy. Stratigraphic contacts are not drawn in areas where interpolated surfaces (i.e. top and bottom) have uncertainties greater than ± 50 m. A similar filter is applied to temperature (areas with uncertainty greater than 50°C have been removed). Only surface manifestations and geothermal wells within a perimeter of ± 100 m have been projected onto the cross section. Maximum depth is 2700 m.

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