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Kriging predictions of drill-hole stratigraphy and temperature data from the Wairakei geothermal field, New Zealand: Implications for conceptual modeling

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ABSTRACT

Drill-hole temperature and stratigraphic datasets from the Wairakei geothermal field were used for geostatistical predictions using Kriging. In order to adequately constrain Kriging models, anisotropy and trends associated with temperature and stratigraphy were studied using standard variogram analysis, in combination with new regional and local structural data, revised gravity, and available geoscientific and reservoir data. This combined analysis lead to the incorporation of horizontal anisotropy (horizontal to vertical correlation ranging from 8:1 for regional stratigraphic units to 4:1 for local rhyolite bodies) in the case of stratigraphic models and variable anisotropy in the case of temperature models. In the latter, the variable anisotropy was represented by two end members: an isotropic model (horizontal to vertical correlation of 1:1) representative of depths >2000 mGL, and an anisotropic model (horizontal to vertical correlation of 3:1) representative of depths <1000 mGL. Kriging models of temperature also incorporated a vertical trend which is a combination of two end members at Wairakei: Boiling-Depth-Point Curve (convective) and linear (conductive). The Kriging models succeeded in identifying the primary geological controls on temperature distribution: major upflows largely controlled by structures at depth (>1000 m depth) and shallow (<1000 m depth) outflows stratigraphically channelled through formation contacts and rhyolite edges. A combination of stratigraphy and faults explain local cold downflows in shallow (750–1000 m depth) parts of the field.

1. Introduction

The Wairakei geothermal field, New Zealand, was the first liquid-dominated reservoir in the world to be developed for electricity generation, with production starting in 1958. At present, Wairakei continues to generate electricity with an installed capacity of approximately 170 MWe, and it is projected to exceed the 300 MWe mark by 2013. The expansion of a geothermal field invariably poses challenges in terms of the definition of production and injection drilling targets, both of which are equally important in the current scheme of sustainable development of geothermal resources. Conceptual models of geothermal reservoirs play a central role in the definition of drilling strategies, and also dynamically evolve as more drill-hole data becomes available. As a result of long-term production at Wairakei, drill-hole datasets have become increasingly available to assist the elaboration of geological conceptual models and numerical simulations of exploitation effects. Analysis and interpretation of large geothermal drill-hole datasets can be challenging, but multidisciplinary analysis can be optimised by use of geostatistical interpolation techniques (e.g., Fabbri, 2001; Teng and Koike, 2007). In this study, we applied Kriging to drill hole datasets of temperature and stratigraphy for geostatistical modelling to illustrate the utility and limitations of Kriging for prediction of drill-hole parameters at Wairakei, to exemplify the value of existing geoscientific and reservoir knowledge in providing constraints to geostatistical models, and to characterize and discuss correlations between the subsurface temperature and stratigraphy with emphasis in the deep architecture of the field. Geostatistical models are used to predict the value of an attribute in an unsampled location using attribute values known at sampled locations. Statistical confidence of the predictions naturally decreases towards peripheral or deep areas of a reservoir which tend to be less explored. In this context, Wairakei offers a unique opportunity to test geostatistical predictions based on cumulative drilling, geoscientific, and reservoir data.

2. Geology of the Wairakei geothermal field

The Wairakei geothermal field is located in the Taupo Volcanic Zone (TVZ), an extensional volcanic arc that has been active during

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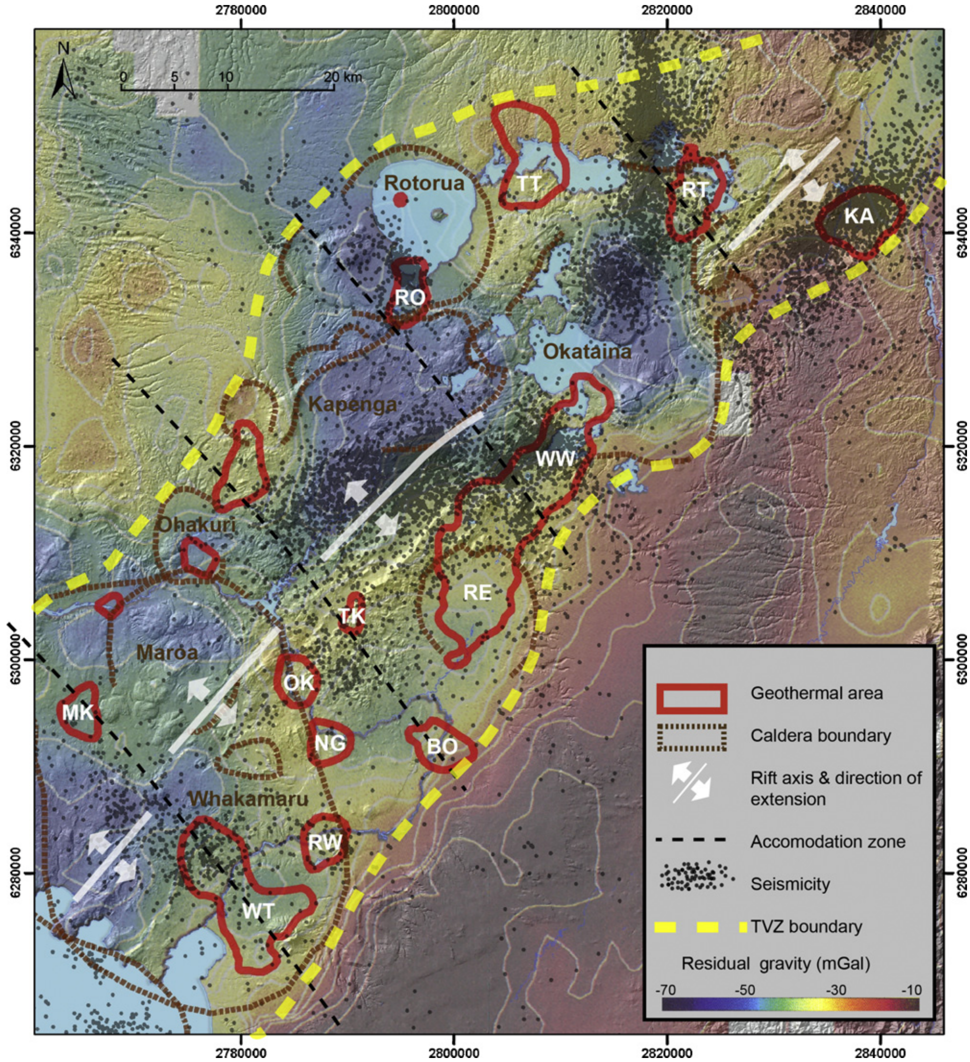

Fig. 1. Map of Central Taupo Volcanic Zone, showing geothermal areas as defined by resistivity data (Schlumberger surveys; 30 Ohm-m boundary from Bibby et al., 1995) with respect to residual gravity anomalies (Bibby et al., 1995), earthquake data (period 1987–2011; 0–5 km depth; source GEONET; data filtered as in Bryan et al., 1999), caldera margins (after Wilson et al., 1995 and Gravley et al., 2007) and the TVZ rift architecture (after Rowland and Sibson, 2004). Base layer is shaded relief map (25 m Digital Terrain Model). Map projection: New Zealand Map Grid (m). Abbreviations for geothermal areas as follows (from north to south): TT = Taheke-Tikitere; RT = Rotoma; KA = Kawerau; RO = Rotorua; WW = Waimangu-Waiotapu; RE = Reporoa; TK = Te Kopia; OK = Orakei-korako; NG = Ngatamariki; BO = Broadlands-Ohaaki; MK = Mokai; RW = Rotokawa; WT = Wairakei-Tauhara.

the last 1.6 Ma (Fig. 1; Wilson et al., 1995; Houghton et al., 1995) in response to oblique subduction of the Pacific plate beneath the Australian Plate. The central segment of the TVZ, extending from Kawerau geothermal field in the north to Lake Taupo in the south (Fig. 1), represents the most active silicic volcanic province on earth (780 km^3/61 kyr), with a number of associated ignimbrite and caldera-forming eruptions, which represent more than 90% of the total erupted magma of the TVZ (Wilson et al., 1995).

The central TVZ marks the concentration of the majority of high-temperature geothermal systems of New Zealand (Fig. 1), with magmatism as the primary heat source. The depth of such heat source remains unconstrained at the scale of individual geothermal systems, but regional seismic and MT studies in the central TVZ identify low resistivity or seismically anomalous regions at depths of ~5 km to >10 km, as an indication of partially molten rock (Sherburn et al., 2003; Heise et al., 2007). It is also worth noting in the explored vertical range of the TVZ (<3 km depth), drilling evidence of magma bodies is lacking and evidence of plutonic rocks is relatively rare (Browne et al., 1992; Milicich et al., 2011).

The central TVZ undergoes NW-SE extension at rates on the order of 7–8 mm/yr, which is mostly accommodated by faulting and tectonic subsidence (Villamor and Berryman, 2001; Nicol et al., 2006). Active structures mainly consist of NE-SW trending, high-angle normal faults, and subvertical tension cracks, which are collectively referred to as rift structures. The spatial relationships between geothermal activity (as delineated by shallow low resistvity anomalies; Bibby et al., 1995, 1998), rift and caldera structures, and modern seismicity (<5 km depth) are shown in Fig. 1. A "TVZ rift boundary" is shown in Fig. 1 to indicate the extent of high-temperature geothermal activity, caldera structures (ca. <330 ka old; Wilson et al., 1995), and active rift structures and tectonic subsidence, mainly interpreted from morpho-tectonic analysis (i.e., surface fault scarps and tracers, and graben structures; Rowland and Sibson, 2004). Earthquake locations (Bryan et al., 1999; Fig. 1) concentrate within the TVZ boundary confirming the potentially active character of most mapped faults. However, earthquake data reveals seismic gaps and NS-trending seismicity clusters (northern part of TVZ; Fig. 1) not coincident with active faults. It is also noted that geothermal locations vary from relatively seismic (e.g., Kawerau) to relatively aseismic (e.g., Ohaaki), and from having strong fault correlation (e.g., Kawerau, Te Kopia; Orakei-korako) to unclear fault correlation (all others). The general observation is that