Geothermics 51 (2014) 182–200

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Heat-producing crust regulation of subsurface temperatures: A stochastic model re-evaluation of the geothermal potential in southwestern Queensland, Australia

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ARTICLE INFO

Article history:
Received 22 August 2013
Accepted 14 January 2014
Available online 8 February 2014

Keywords:
Geothermal
Australia
Heat flow
Thermal conductivity
Stochastic modelling
Inversion modelling

ABSTRACT

A large subsurface, elevated temperature anomaly is well documented in Central Australia. High heat producing granites (HHPGs) intersected by drilling at Innamincka are often assumed to be the dominant cause of the elevated subsurface temperatures, although their presence in other parts of the temperature anomaly has not been confirmed. Geological controls on the temperature anomaly remain poorly understood. Additionally, methods previously used to predict temperature at 5 km depth in this area are simplistic and possibly do not give an accurate representation of the true distribution and magnitude of the temperature anomaly. Here we re-evaluate the geological controls on geothermal potential in the Queensland part of the temperature anomaly using a stochastic thermal model. The results illustrate that the temperature distribution is most sensitive to the thermal conductivity structure of the top 5 km. Furthermore, the results indicate the presence of silicic crust enriched in heat producing elements between 5 and 40 km.

1. Introduction

Elevated geothermal gradients have long been recognised in the Great Artesian Basin (GAB) of central-eastern Australia (Polak and Horsfall, 1979, and references therein) (Fig. 1a). More recently, a regional map estimating the temperature at 5 km depth has been generated (Oztemp) (Somerville et al., 1994; Chopra and Holgate, 2005; Gerner and Holgate, 2010) as a basis for assessing the geothermal energy potential in Australia. The depth of 5 km was chosen as a cut-off for the economic extraction of geothermal energy (Chopra and Holgate, 2005). The map suggests the presence of a large (ca. 800,000 km^2) subsurface temperature anomaly (Oztemp anomaly) across central Australia and SW Queensland (Fig. 1b), with estimated temperatures greater than 235 °C at 5 km depth, ca. 85 °C (i.e., ca. 57%) higher than predicted from the average geothermal gradient for the upper continental crust (Somerville et al., 1994; Chopra and Holgate, 2005).

It is estimated that rocks in the Cooper Basin region, shallower than 5 km, hold ca. 7.8 million PJ available heat (Somerville et al., 1994; Bahadori et al., 2013) (Fig. 1b). Across the continent, Geoscience Australia has estimated that the crust shallower than 5 km contains thermal energy equivalent to 2,500,000 years worth of the total 2004–2005 energy consumption in Australia (Budd et al., 2006). Accordingly, geothermal exploration and development attracted multi-billion dollar work commitments from industry in Australia, with more than 400 geothermal tenements so far granted since 2001 (Dowd et al., 2011).

To date, generation of electricity from geothermal energy in central Australia and SW Queensland is limited to the 80 kWe (net) Birdsville geothermal plant (Bahadori et al., 2013) operating since 1992, a 20 kWe plant that operated on Mulka cattle station in South Australia (Lund and Boyd, 1999) for a short time from 1987, and a 1 MWe pilot plant commissioned by Geodynamics Ltd at Innamincka in May 2013. Recently, larger-scale projects have focused on Engineered Geothermal System (EGS) development at Innamincka, South Australia (Fig. 1b), where high heat producing granites

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http://dx.doi.org/10.1016/j.geothermics.2014.01.005

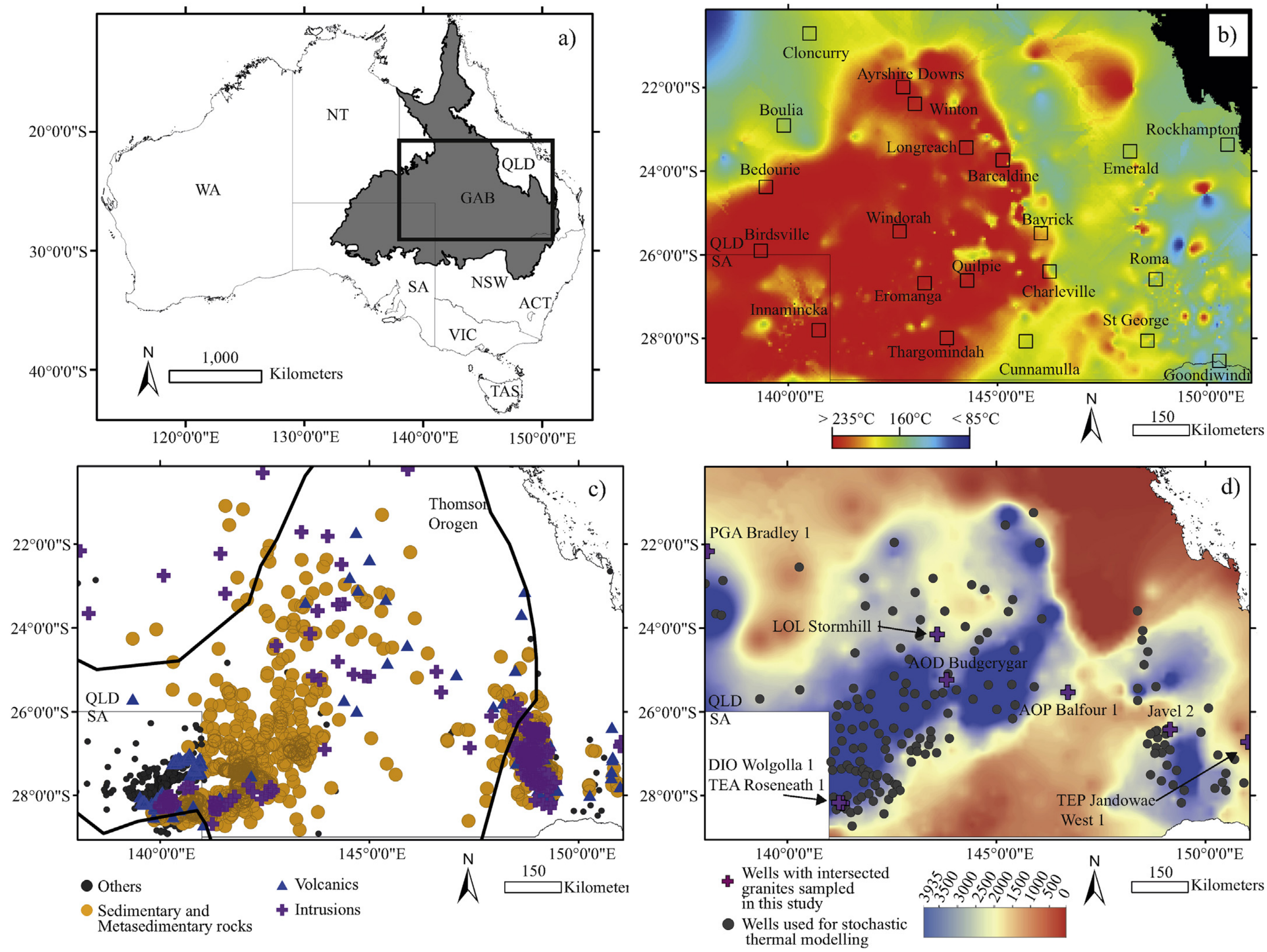

Fig. 1. Summary of the geological features of the area of study in SW Queensland. The scale is the same for (b–d). (a) Outline of the study area; GAB is Great Artesian Basin, WA is West Australia, SA is South Australia, QLD is Queensland, NSW is New South Wales, VIC is Victoria, NT is Northern Territory and ACT is Australian Capital territory; (b) Oztemp map with towns and locations referred to in text; after Holgate and Gerner (2011); SA and QLD indicates the state border between South Australia and Queensland. (c) Nature of the intersected basement using data from Brown et al. (2012) for Queensland and available information from https://sarig.pir.sa.gov.au/Map for South Australia; (d) depth to basement (modified after Purdy et al., 2013) and location of new data generated in this study. Purple crosses indicate the location for new thermal conductivity and heat production values and grey points correspond to new temperature and heat flow data at 5 km depth.

(HHPGs) are intersected at 3–5 km depth. In particular, heat flow studies indicate that the high temperatures observed at Innamincka are related to release of heat generated by radioactive decay within HHPGs at depth, below a thermally insulating sedimentary cover (Middleton, 1979; Gallagher, 1987; Beardsmore, 2004). It has thus been similarly predicted that anomalously high temperatures in SW Queensland (Fig. 1b) also result from subsurface HHPGs (e.g., Chopra and Holgate, 2005; Draper and D'Arcy, 2006). However, heat production values estimated from limited whole-rock chemical data for the few granites (Champion et al., 2007) intersected in petroleum wells to depths of ca. 3 km are substantially lower (1.6–4.2 $\mu W\,m^{-3}$) than those estimated for granites at Innamincka (9.7 $\mu W\,m^{-3}$ for the Big Lake Suite Granite; Middleton, 1979).

Given the apparent absence of HHPGs (at <5 km depth) beneath large tracts of the Oztemp anomaly, an important issue for geothermal energy assessment across this region is a critical appraisal of the quality of data upon which the temperature map was based. Important issues with the current Oztemp map are the use of: (1) linear extrapolations of borehole temperature measurements, as this may introduce errors because a conductive steady state temperature profile of continental crust must be non-linear in the presence of radiogenic material; (2) unreliable, shallow (e.g., <500 m) temperature measurements extrapolated to 5 km depth, because shallow temperatures could be affected by past climatic variations (e.g., Bauer and Chapman, 1986); and (3) temperature extrapolations without considering material properties of the intersected lithologic formations, in particular, thermal conductivity and heat production of the rocks (e.g., Chapman, 1986).

The availability of heat flow data in Australia and across the GAB are limited with only two heat flow values reported for the Queensland part of the Oztemp anomaly (Gallagher, 1987; Goutorbe et al., 2008). Additional heat flow data have been measured at the continental scale using a linear relationship between the silica geothermometer and heat flow (Pirlo, 2002). However, the distribution of these values is heterogeneous across SW Queensland. Other heat flow determinations across the Oztemp anomaly are restricted to the South Australian part of the Cooper Basin (Beardsmore, 2004; Meixner et al., 2012). Consequently, the foundations of the Oztemp anomaly for SW Queensland are based on sparse surface heat flow data and currently, little evidence for buried high heat producing granitic rocks at depth.