Geothermics 51 (2014) 496–508

Contents lists available at ScienceDirect

Geothermics

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

Estimation of the deep geothermal potential within the Tertiary Limagne basin (French Massif Central): An integrated 3D geological and thermal approach

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ARTICLE INFO

Article history:
Received 30 November 2012
Accepted 6 February 2014
Available online 4 April 2014

Keywords:
Geothermal potential
Resource assessment
3D modelling
Geological modelling
Thermal modelling
Limagne, France

ABSTRACT

The geothermal potential of a deep sedimentary-rock reservoir, in a Tertiary graben, the Limagne d'Allier basin (Massif Central, France), is assessed. The most interesting geothermal target is identified as a thick basal Tertiary sandstone overlying crystalline Paleozoic basement. The total amount of recoverable energy in this clastic aquifer is estimated at over 500 PJ (500×10^{15} J) in the modelled area. The most promising zones appear along the north-western edges of the basin, where sediment infill is thickest. The methodology used for estimating geothermal potential starts from geological field data. The first step is to obtain a better understanding of the structure and geometry of the target zone, using various data such as field measurements, and borehole and geophysical data. These data are reinterpreted through the construction of a 3D geological model. Inconsistencies are checked and turned into a coherent 3D interpretation. The second step consists in meshing the geological model into an unstructured 3D finite-element mesh where realistic thermal boundary conditions are applied. The temperature field is computed in a third step. The thermal calculation is achieved by assuming a purely conductive behaviour and through comparison with existing borehole profiles. The computed temperatures fit the measurements in the deepest part of the Limagne d'Allier basin, while the potential role of fluid flow is highlighted in its upper part, either within more permeable formations, or around the boreholes. A fourth, final, step maps the geothermal potential (recoverable energy) in the deepest part of the Tertiary graben, where the total amount of geothermal energy available is calculated. The result of this work provides valuable guidelines for geothermal exploration in the area and our methodology can be replicated elsewhere.

1. Introduction

The Limagne d'Allier basin is located in a promising zone for geothermal energy (Hurtig et al., 1991). This Tertiary basin has never been exploited for its geothermal resource, but has been investigated since the 1970s for this purpose (Gable, 1978; Géoservices, 1979; Geotherma, 1981). In recent years, a revival of geothermal exploration and permit deposits has taken place in this basin. However, none of the existing studies tackled the problem of estimating the recoverable energy, as no detailed 3D geological structure was available. Our aim is thus to improve the 3D thermal characterization of the Limagne basin and to give an estimate of its geothermal potential, paying special attention to the role of the local hydrological regime in the creation of thermal anomalies.

Two major aspects must be considered for geothermal exploration. First, good understanding of the geological structure is indispensable for determining whether an area may host geothermal resources (Teng and Koike, 2007; Calcagno et al., 2012). Suitable exploration methods were described in detail by Bruhn et al. (2010), emphasizing the major role of delineating suitable geological settings for geothermal exploration. Second, inferring the available energy is a guide for estimating the viability of the geothermal resource (Lavigne, 1978; Muffler and Cataldi, 1978; Jung et al., 2002; Kohl et al., 2003; Dezayes et al., 2008). In some studies, temperature simulation or geothermal potential estimation is based on the cradle of a data-constrained geological description (Mottaghy et al., 2011; Scheck-Wenderoth and Maystrenko, 2013; Kastner et al., 2013). However, geological

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http://dx.doi.org/10.1016/j.geothermics.2014.02.002
0375-6505/

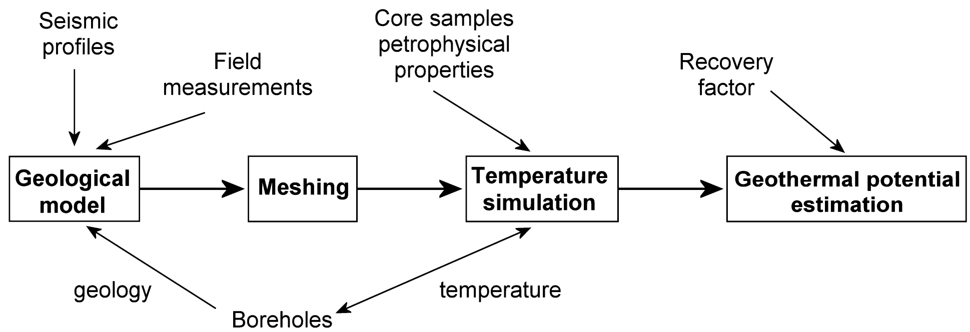

Fig. 1. Proposed workflow for estimating geothermal potential from field data.

interpretation and estimation of the geothermal potential are often disconnected. We thus propose an integrated 3D methodology for estimating the geothermal potential, taking into account a coherent and well-constrained interpretation of the geological structure. This integrated methodology consists in the four steps shown in Fig. 1:

1. A coherent 3D geological interpretation uses field-, borehole-, and seismic data.
2. The geological model is turned into a mesh where thermal boundary conditions are applied to prepare the temperature computation.
3. The 3D temperature model considers geological structure and thermal properties of the rocks.
4. Finally, the geothermal potential is calculated in 3 dimensions by taking into account the volumes of the rocks, the temperature field, and a recovery factor applied to the heat in place.

In the following sections, the geological and thermal settings are presented before describing the data. Then, each step of our integrated methodology is detailed and the results are shown. As a final point, both methodology and results of our study are discussed.

2. Geological and thermal settings

Located north of Clermont-Ferrand, France, the Tertiary Limagne d'Allier basin is roughly north-south oriented and is bounded by regional faults (Fig. 2). From the Late Eocene to the Oligocene, a half-graben was formed due to progressive subsidence resulting from extension within the West-European plate.

The Limagne d'Allier basin is delimited by the Clermont-Ferrand fault to the west and by its northern prolongation, called the Aigueperse fault (see Fig. 2 for locations). Both faults have a normal throw of several hundred metres; the Aigueperse fault has also a strike-slip component and is well-known for its recent seismogenic activity. The structural configuration of both faults is at the origin of the deepest part of the basin located around the town of Riom. Seismic-line interpretation indicates that most of the faults within the basin had no clear vertical displacement after the Oligocene, but historic seismicity data for the two main bordering faults show evidence of more recent movement. Overlying the Limagne d'Allier basement, four main sedimentary sequences, labelled S1 to S4, fill the basin: Middle Eocene (S1), Upper Eocene (S2), Rupelian (S3) and Chattian (S4). Each sequence is composed of a sedimentary cycle ranging from detrital formations at the base ("Reservoir"), followed by alternating layers of detrital and carbonate sediments ("Intermediate"), and capped by marl and carbonate deposits at the top ("Top").

The area was selected and investigated for several large-scale geological features. First, this area is a Tertiary graben belonging to the Western European Rift System with a rather shallow Moho (<30 km depth). Most of these grabens in Europe show promising geothermal gradients in the shallow sediments, as well as highly fractured zones in the deep underlying basement (Genter et al., 2003a, 2010). Second, many thermal springs occur along the graben border faults, indicating potential hydrothermal circulation (Millot et al., 2007). Third, there was some recent volcanic activity (<4000 y B.C.) that might represent an additional heat source.

In view of these geological features, the area was explored for oil and gas until the 1980s. The Limagne d'Allier basin has been also studied for its geothermal potential for many years (Gable, 1978; Géoservices, 1979; Geotherma, 1981; Genter et al., 2003a,b, 2005; Bouchot et al., 2008). Fig. 3 shows that the temperature extrapolated to 5 km depth in the modelled area is anomalously high, as confirmed by a detailed analysis in Genter et al. (2003a). The original map (i.e. Fig. 3 without coloured ellipses) was based on a temperature atlas of subsurface temperatures (Hurtig et al., 1991), where several uncertainties were not discussed. These and the subsequent subsurface temperature maps were built with downward extrapolation of available temperature data, and correspond to a collage of individual national maps, thus involving several sources of uncertainties (Hurter and Schellschmidt, 2003). Genter et al. (2003a) used published data on equilibrium-temperature gradients to check the suggested temperatures at 5 km depth. A linear extrapolation from the deepest temperatures was assumed. It turned out that the Limagne basin actually is probably hotter (see red ellipse in Fig. 3) than previously assumed, with temperatures possibly exceeding 240 °C at 5 km depth.

3. Data

3.1. Structural data

Among the existing wells within the Limagne d'Allier basin, eighteen are located in the study area (Fig. 2). Most of them reach formations older than S4 and a few reach the basement, such as the Croix-Neyrat and Beaumont boreholes (see Section 3.3). The geology of these 18 wells was reinterpreted in terms of lithofacies and sequence stratigraphy. A database with the thickness of each lithofacies was constructed and used for the geometrical modelling. In this area, several seismic campaigns were conducted as well for oil and uranium exploration from 1958 to 1979. Fig. 2 shows the location of the existing seismic profiles re-used for our study. In particular, 26 seismic profiles were calibrated on borehole data, digitized and reprocessed before their reinterpretation; three main geological interfaces acting as seismic reflectors were identified as well as several normal faults. The reflectors shown in Fig. 4 correspond to an intra-Eocene interface (S2_Intermediate), the top of the Eocene (S2_Top) and the Rupelian top of the Oligocene (S3_Top).