Journal of Applied Geophysics 92 (2013) 30–38

Contents lists available at SciVerse ScienceDirect

Journal of Applied Geophysics

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

Interpretation of gravity data to delineate structural features connected to low-temperature geothermal resources at Northeastern Portugal

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ARTICLE INFO

Article history:
Received 4 December 2012
Accepted 11 February 2013
Available online 24 February 2013

Keywords:
Gravity data
Bouguer anomaly
Gravity derivative
3D inversion
Hydrothermal system
Portugal

ABSTRACT

A great number of low-temperature geothermal fields occur in Northern-Portugal related to fractured rocks. The most important superficial manifestations of these hydrothermal systems appear in pull-apart tectonic basins and are strongly conditioned by the orientation of the main fault systems in the region. This work presents the interpretation of gravity gradient maps and 3D inversion model produced from a regional gravity survey. The horizontal gradients reveal a complex fault system. The obtained 3D model of density contrast puts into evidence the main fault zone in the region and the depth distribution of the granitic bodies. Their relationship with the hydrothermal systems supports the conceptual models elaborated from hydrochemical and isotopic water analyses. This work emphasizes the importance of the role of the gravity method and analysis to better understand the connection between hydrothermal systems and the fractured rock pattern and surrounding geology.

1. Introduction

There is a great scientific and economic interest in surface manifestations of geothermal fluid circulation all over the world. Hydrogeological, geochemical, isotopic, and geophysical data are commonly used to construct an image of geothermal systems, enabling decision making regarding important issues that will influence the development of the future exploitation of such resources (Dickson and Fanelli, 2003).

Low-temperature geothermal fields occur in Northern Portugal (Marques et al., 2010) associated with highly fractured rocks. The area under study is a part of the large morphostructural unit called *Hesperic* Massif, in the *Galicia-Trás-os-Montes* Zone (Fig. 1). This region shows evidences of multiple deformation events compatible with the Hercynian cycle, which comprises three deformation phases, and also with the alpine cycle (Ribeiro, 1974). Several authors (e.g. Arthaud and Matte, 1975; Ribeiro et al., 2007) outline three main Late-Variscan strike–slip fault systems in the northern sector of Iberia: the dominant NE-NNE (always sinistral), the subordinate NW-NNW (Late-Variscan dextral) and the conjugate E-ENE (mainly sinistral). The geometry and kinematics of the N–S maximum compressive stress field were responsible for the development of the process of active deep-crustal shortening and related main geomorphic patterns in Iberia (Vicente and Vegas, 2009). There are also evidences of neotectonic activity in the more recent sedimentary formations.

Fig. 2 shows a sketch of the geological setting of the area. The schist–graywacke complex (SGC) is the oldest identified unit (ante-Ordovician) (Pereira, 2006). It was formed by the deposition of a sedimentary sequence in the intracontinental trench related to the distensive process of oceanic birth. When the tension field changed from a distensive to a compressive regime, these sedimentary sequences were deformed originating the now schist–graywacke complex.

The schist, graywacke and psammite complex (SGP) dates from the lower Siluric (Ribeiro, 1974), while the turbiditic sequence of the Santos e Curros Formation (T) was deposited in the lower Devonic (Pereira, 2006). By the end of the Hercynian cycle, episodes of magma ascension occurred, resulting in the installation of granitic formations (STG). These formations are, for the most part, syntectonic with the third deformation phase of the Hercynian orogeny (D3). However there are occurrences, in circumscribed masses, of apparently post tectonic granites (PTG). In fact, these granites do not present evidences of intersection with D3. Their installation is related to a tardi-Hercynian fracturation trending NNE–SSW (Pereira, 2006).

The main geologic feature present in this area is the segment of the NNE–SSW Penacova-Regua-Verin fault (PRVf) zone (Baptista, 1998; Cabral, 1995; Lourenço, 2006). This structure stretches for 200 km, from Penacova to the south, northward to Verin, Galicia. In tardi-

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http://dx.doi.org/10.1016/j.jappgeo.2013.02.011

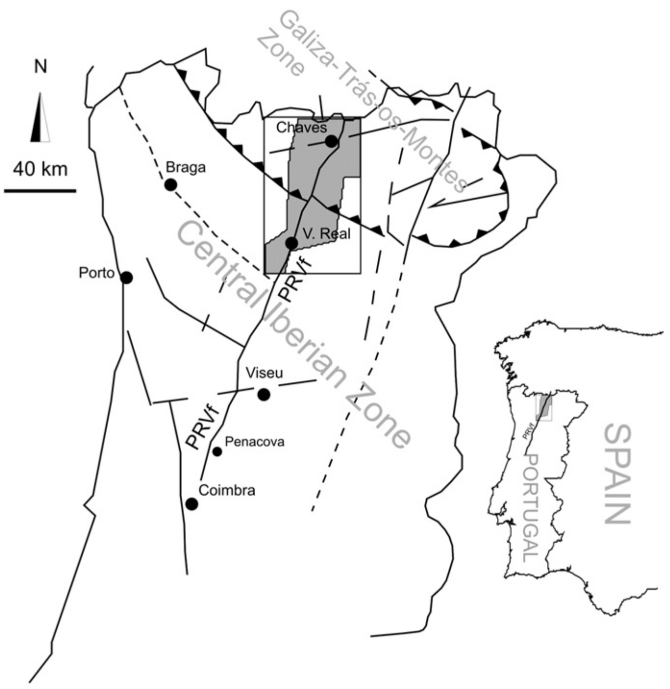

Fig. 1. Location of the gravity survey in the Galicia-Trás-os-Montes zone. General location of the Penacova-Régua-Verin fault (PRVf).
Adapted from Ribeiro et al., 1979.

Hercynian time, the region was cut by a network of strike–slip faults showing two conjugate systems, one sinistral with directions NNE–SSW to ENE–WSW, another dextral with direction NNW–SSE to NE–SE (e.g. Lourenço, 2006; Ribeiro, 1974). This kinematic indicates a sub-horizontal maximum compression with an approximate orientation N–S. There are evidences that these fault systems have been activated during the compressive events of the Alpine cycle. These reactivations resulted in complex movements that globally reflect the accommodation of the deformation conditioned by preexisting discontinuities. This resulted in the development of a series of subsidiary pull-apart and push-apart structures like horsts and grabens (e.g. Baptista, 1998). Examples of these structures are the tectonic depressions present in the area, like the Chaves, Telões and Vila Real basins. These depressions were later filled with Miocene–Pleistocene sedimentary series (lacustre, alluvial, detritic, etc.).

The low-temperature geothermal fields in Northern Portugal are strongly connected to the NNE–SSW and NNW–SSE fault systems. These fractured areas favor the circulation of fluids, allowing for the infiltration and later ascension of the altered fluid. The areas where those crossing fault systems have a good permeability allow a fast path for the up flow of hot water. This process results in the occurrence of several hot water springs. In the Chaves basin the vertical movement should be fast, since a decreasing of 37% in water temperature is estimated. At Vidago and Pedras Salgadas the up flow should be slow allowing the thermodynamic water–rock equilibrium. That is the reason why those waters are cold.

The gravity survey presented in this work is the only geophysical study carried out that allows a regional overview of the area. The only other existing geophysical data are too local and shallow to be of any use for this purpose (see e.g. Lourenço, 2006; Monteiro Santos et al., 1995, 1996; Represas et al., submitted for publication). Even though the gravity data is suitable for the interpretation of regional structures, the sparse distribution of the gravity stations in most parts of the surveyed area does not tolerate more detailed interpretations. In particular, it is not possible to detect and interpret hydrothermal alterations associated with hot water circulation near known springs.

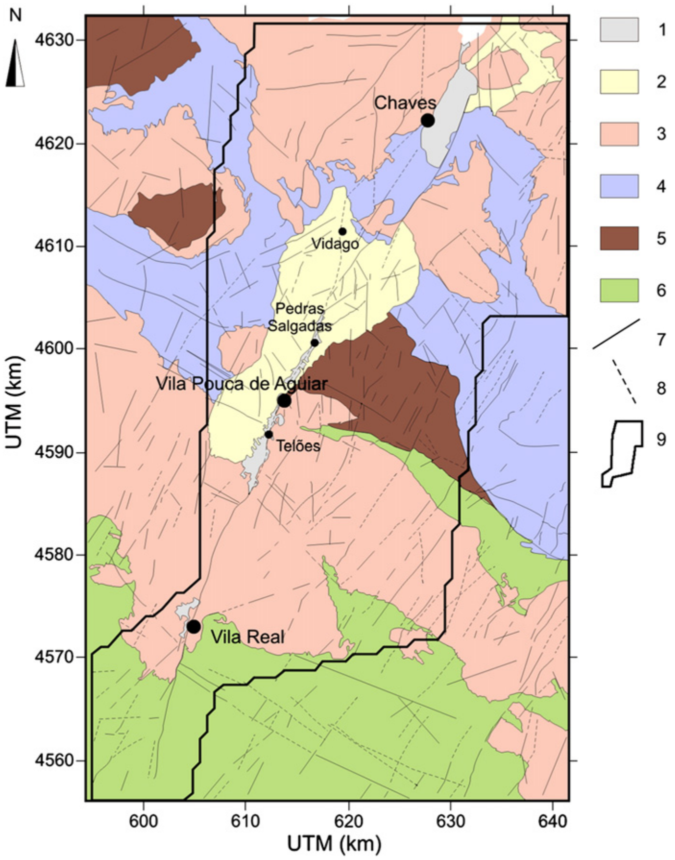

Fig. 2. Geological overview of the area covered by the gravity survey, adapted from the 1:200,000 geological map published by IGM (Pereira, 2006). 1 — Sedimentary cover (Q), 2 — Post-tectonic medium to fine grained granite (PTG), 3 — Syn-tectonic medium grained granite (STG), 4 — Phylites, quartzites, carbonaceous slates (SGP), 5 — Turbiditic sequence (T), 6 — Schist–graywacke complex (SGC), 7 — Mapped fault, 8 — Probable fault, 9 — Outline of the area covered by the gravity survey.

2. Gravity survey

2.1. Data acquisition and reduction

The gravity survey was carried out in two distinct periods of time, one in the late 1980s and another in early 1990s. The first measurements were made with a Worden Master gravimeter, while in the later measurements a Lacoste & Romberg gravimeter was used. The combination of the measurements carried out in both events comprises 5647 stations covering an area of approximately 1580 km^2. Fig. 3 shows the distribution of the gravity survey points. The spacing between stations varies between 400 m and 1000 m, depending on the accessibility of the terrain. The Chaves gravimetric base station (Instituto Geográfico Cadastral — IGC) was used to correct relative values to absolute gravity. For all data points the elevation was measured using a micro barometer "Barolux" and a micro barometer "Fuess" for tide control. Elevation values were confirmed using topographic maps (scale 1:25,000). It was estimated that these values have an error of ±2 m.

Free air and Bouguer corrections were calculated using the International Association of Geodesy 1967 formula and an average crustal density of 2.67 g/cm^3. Topographic corrections were calculated using the "Hammer" method over the 1:25,000 topographic maps.

To facilitate the analysis, the most relevant lithological contacts, considering the scale of the survey, were superimposed on the complete Bouguer anomaly map shown in Fig. 4. The north panel is dominated by a strong negative anomaly (−58 to −66 mGal) aligned along a NNE–SSW direction. This anomaly coincides with the location of the quaternary sedimentary deposits of the Chaves basin (Represas et al.,