A METHODOLOGY FOR THE ASSESSMENT OF LOW-TEMPERATURE GEOTHERMAL SYSTEMS (N-PORTUGAL): THE "*EYES*" OF GEOSCIENCES

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1. Introduction

The aim of this work is to provide a methodology for the assessment of low-temperature geothermal resources, based on some case studies in the Portuguese mainland. For this purpose, a multidisciplinary approach applied to Chaves geothermal system will be presented. Several disciplines of Geosciences should be applied to build up a conceptual model of a given low-temperature geothermal system, allowing important decisions to be addressed in order to sitting future deep drilling operations (*e.g.* Haenel and Hurter, 2002; Dickson and Fanelli, 2003). Geologic, geodynamics, hydrogeological, geochemical, isotopic (*e.g.* δ^2H, $\delta^{18}O$, $\delta^{13}C$, ^3H, ^{14}C and $^3He/^4He$) and geophysical exploration data, when used in parallel, can provide key information on origin and "*age*" of the geothermal waters, underground flow patterns and the net fracture draw and water-rock interaction occurring at depth. Heat flow measurements and the assessment of geothermal gradients are essential aspects of geothermal resources investigation, providing a good estimate of the temperature at the top of the reservoir (Haenel and Hurter, 2002). In this paper, the methodological approach, some of the results obtained so far, as well as new achievements, will be presented and discussed.

2. Methodological approach

2.1. Geology, geodynamics and hydrogeology

Geology is a science dealing with the Earth crust, the materials it is made of and the processes that influence it. Nowadays, geology is a multifaceted discipline, including the knowledge of soils, minerals and rocks developing in the historical process and their present characteristics and environmental issues. The first step in the assessment of the geological and geodynamic setting of a given low-temperature geothermal resource is the assemblage of all available data of the region from all possible sources: national or regional surveys, land owners, the oil and gas industry, downhole temperature data, published academic data, and remote sensing data. Such a data compilation is usually an inexpensive but potentially time-consuming part of the exploration process (*e.g.* Ernst, 2010). Careful consideration should be put on the geologic setting, including heat flow, stratigraphy, and structural framework. Studying the geochemistry of geothermal fluids together with geophysical data provides knowledge and skills for detecting the kind of geological formation percolated by the geothermal fluids, including important information about water-rock interaction processes occurring at depth (*e.g.* Marques et al., 2010a,b; Ernst, 2010). This information could have crucial meaning in understanding global geothermal processes in a given geothermal field. Recovering of historical events could be the clue to solve questions ascribed to present-day geothermal events. From the hydrogeological point of view, fractures and discontinuities are amongst the most important geological structures. Most rocks have fractures and other discontinuities which make possible storage and movement of fluids through them. Main flow paths in fractured rocks are along joints, fractures, shear zones, faults and other discontinuities (*e.g.* Singhal and Gupta, 2010). The discharge zones are mainly related to the intersection of the main local/regional deep-crust fault lineaments (and conjugate structures), responsible for creating the geothermal waters ascent. High permeability is vital for a conventional geothermal system. Exploration strategies must target accessible and extractable sources of geothermal water in large enough quantities to promise sustainable power and/or heat extraction (Dickson and Fanelli, 2003).

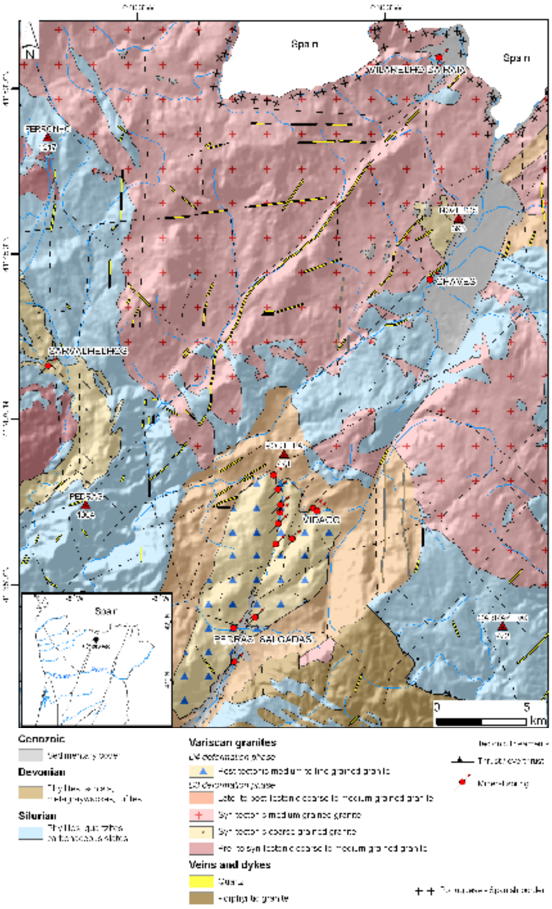


Fig. 1 - Regional geological map of the Chaves region (N Portugal), showing the location of Vilarelho da Raia, Chaves, Vidago and Pedras Salgadas CO_2-rich mineral waters (Geological base: adapted from SGP, 1992). After Marques et al. (2010a).

Concerning fracture and main structural features in Portugal, Arthaud and Matte (1975) consider three Late-Variscan strike-slip fault systems in the northern sector of Iberia: the dominant NE-NNE (always sinistral), and the subordinate and conjugate NW-NNW (Late-Variscan dextral) and the E-ENE (mainly sinistral). From this geometry and kinematics, they concluded that an N-S maximum compressive stress field was responsible for the development of the whole fracture/faulting network in Iberia, which is responsible for the numerous hydrothermal systems occurring northern Portugal. The Chaves low-temperature (issue temperature of 76ºC) geothermal system (Fig. 1), is located in the N part of the country occurring along or near one of the most important NNE trending sinistral fault, the so-called Verin-Régua-Penacova fault zone (Cabral, 1989; Ribeiro et al., 1990, 2007).

The study region consists mainly of Variscan granites and Paleozoic metasediments (predominantly, phyllites, quartzites, schists). The most recent formations are Miocene-Pleistocene cover sediments showing their maximum development along the central axis of Chaves graben (Fig. 1). The Alpine Orogeny has caused extensive tectonic features responsible for the formation of several hydromineral systems. Vidago and Pedras Salgadas areas, rich in cold (17ºC) mineral waters, are also composed of Variscan granites with some outcrops of metamorphic rocks of Silurian age covered by Cenozoic deposits. According to Baptista et al. (1993) and Sousa Oliveira and Portugal Ferreira (1996), in the study area, Chaves is the only site where geothermal waters issue most probably favoured by i) high relief (tectonic throw), ii) deep fracturing and iii) thickness of graben filling sediments.

2.2 Geochemistry and isotopes

Geochemical and isotopic methods are frequently used in prospecting low-temperature geothermal systems (Ellis and Mahon, 1977; I.A.E.A., 1981), being also applied as an important guide for decision making on subsurface exploration by drilling. Geochemical and stable isotopic signatures (δ^2H, $\delta^{18}O$) of geothermal waters are useful to provide information on the origin of waters, recharge areas and underground flow patterns, and may allow an evaluation of the subsurface water-rock interaction processes (*e.g.* I.A.E.A., 1981; Marques et al., 2006). ^3H concentrations in geothermal waters are utilized to identify the presence of recent recharge. Geothermal water "*apparent ages*" can also be estimated from ^{14}C concentrations. Nevertheless, geothermal water dating with ^{14}C is complex since it's not easy to know exactly what proportion of C is derived from the atmosphere or the soil, and from rock carbonates or possibly mantle sources (*e.g.* Carreira et al., 2008). $^3He/^4He$ and $^{13}C/^{12}C$ isotopic ratios of the gas phase ascribed to the geothermal waters are used to distinguish between deep crustal fluids and mantle volatiles released along the local/regional tectonic lineaments (*e.g.* Pérez et al., 1996; Carreira et. al., 2010).

Chemical geothermometry is applied to infer reservoir temperatures (*e.g.* Ellis, 1970; Fournier, 1977). However, mixing processes with shallow groundwaters in upflow zones may change the chemical signatures of deep fluids, and therefore the results of the geothermometers should be interpreted with caution. Sometimes, the signatures of the deep geothermal fluids can be assessed indirectly from their effects on the surrounding rocks (hydrothermal alteration), providing information on the chemical and isotopic composition of the geothermal waters and natural evolution of geothermal systems (*e.g.* Taylor, 1978; Petrucci et al., 1993; Marques et al., 2010b).

The Chaves low-temperature geothermal waters (Fig. 1) belong to the HCO_3/Na/CO_2-rich type (with pH ≅ 7). Temperature and TDS values range between 48ºC - 76ºC and 1600 mg/L - 1850 mg/L, respectively. Free CO_2 is of about 350 - 500 mg/L. In the case of Vilarelho da Raia, Vidago and Pedras Salgadas HCO_3/Na/CO_2-rich mineral waters (Fig. 1) water-rock interaction is enhanced by low temperatures since the solubility of (deep) CO_2 in water increases with decreasing temperature, explaining why some of the most mineralised waters in the region are the cold waters (*e.g.* Marques et al., 2010a,b). The $\delta^{18}O$ and $\delta^{2}H$ values of Chaves low-temperature geothermal waters lie on or close to the Global Meteoric Water Line ($\delta^2H = 8\delta^{18}O + 10$) defined by Craig (1961), indicating that they are meteoric waters which have been recharged without evaporation. The local shallow cold dilute groundwaters related to sampling sites located at high altitudes show depleted $\delta^{18}O$ and $\delta^{2}H$ values similar to those of Chaves low-temperature geothermal waters (Aires-Barros et al., 1995). The low $\delta^{18}O$ values of Chaves low-temperature geothermal waters require that these waters were derived from meteoric waters at more than 1150 m a.s.l.. These elevations (Fig. 1) are obtained in the Padrela Mountain (NE-Chaves), which presumably feeds the local infiltration (Marques et al., 2006). The ^{14}C activity (from 4.3 up to 9.9 pmC) determined in some of the cold CO_2-rich mineral waters from Vidago and Pedras Salgadas region is incompatible with the systematic presence of ^{3}H (from 1.7 to 7.9 TU). Those cold CO_2-rich mineral water displaying the highest ^{3}H content should be faced as youngest groundwaters, ascribed to shorter and shallower underground flow paths (Carreira et al., 2008). The $^{3}He/^{4}He$ ratios found in the gas phase of the CO_2-rich waters range between 0.89 and 2.68 times the atmospheric ratio (Ra), at Chaves and Pedras Salgadas, respectively. These ratios are higher that those expected for a pure crustal origin (~0.02 Ra). The $\delta^{13}C$, varying between -7.2 and -5.1 ‰ vs. PDB, and the $CO_2/^{3}He$ values, from 5.1×10^8 to 7.5×10^9, are typical of MORB fluids (Marques et al., 2006; Carreira et al., 2010). In the case of Chaves low-temperature CO_2-rich geothermal waters the results SiO_2 and K^2/Mg geothermometers are in fair agreement, indicating equilibrium temperatures around 120ºC. Considering the mean geothermal gradient of 30ºC/km (Duque et al., 1998). Considering that:

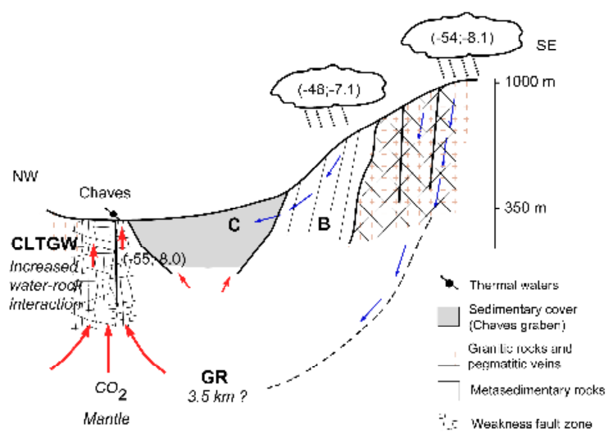
$$depth = (T_r - T_a) / gg$$

where T_r is the reservoir temperature (120ºC), T_a the mean annual air temperature (15ºC) and gg the geothermal gradient (30ºC/km) one can estimate a maximum depth of about 3.5 km reached by the Chaves water system.

2.3 Geophysical exploration data

The geophysical methods are aimed at providing information about a possible geothermal reservoir, the heat source, and the hydraulic state (*e.g.* Griffith and Barker, 1993). Geophysical methods could additionally help to obtain accurate information about the structural and tectonic setting, the regional and local stress field, and other parameters in a depth range up to several kilometres (*e.g.* Ernst, 2010). Electromagnetic methods can be used for exploration circulating fluids in reservoirs or faults, supplying important information about their activity and fluid content. The presence of geothermal fluids in fractured rocks can result in resistivity changes that are more than one order of magnitude greater than those measured in intact rocks (*e.g.* Ernst, 2010).

At the Chaves low-temperature geothermal field (Fig. 1) resistivity surveys included 29 Schlumberger vertical electrical soundings (VES), dipole-dipole lines, pole-dipole-lines, magnetotellurics and rectangle surveys (Monteiro Santos et al., 1996, 1997). The inversion results of the VES and audio-magnetotellurics were combined to obtain a map of the low resistivity layer associated with the geothermal reservoir. Resistivity cross-sections along N-S and E-W directions were obtained (Monteiro Santos et al., 1995), showing that conductive zones are concentrated in the central part of the graben as a result of high temperatures combined with the high salinity of the hot waters in fractured and permeable rock formations. The meteoric waters infiltrates on the highest topography, where rainfall is important, percolates at great depth along the open fault system and then emerge in a discharge area at lower altitude on the Chaves plain (Fig. 2). The deep-seated CO_2 seems to be transported from



its mantle source to the surface by migration as a separate gas phase, being incorporated in the infiltrated meteoric waters at considerable depth in the case of the Chaves low-temperature CO_2-rich geothermal waters.

3. Concluding remarks

This work summarizes the results of geologic, geodynamics, hydrogeological, geochemical, isotopic and geophysical exploration data in low-temperature geothermal resources assessment. The local/regional high altitude sites associated with highly fractured rocks play an important role in conducting the infiltrated meteoric waters towards the discharge zones. The discharge zones are related to the intersection of the major regional deep fault structures responsible for the geothermal fluids ascent. Isotopic signatures of C present in these waters systems indicate a deep-seated (upper-mantle) origin for the CO_2. It is expected that the results achieved in this paper may lead to an increased interest by the local Authorities in prospecting "*new*" geothermal resources in the studied region, which may potentially lead to the development of deep drilling strategies.

Fig. 2 - Conceptual circulation model. CLTGW stands for Chaves low-temperature geothermal waters; GR stands for geothermal reservoir; in brackets the values stands for (δ^2H; $\delta^{18}O$). Adapted from Aires-Barros et al. (1995).

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