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Hydrogeochemistry and geothermometry of thermal water from north-eastern Algeria

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ABSTRACT

This paper deals with the results of a hydrochemical and geothermal study of thermal waters in northeastern Algeria. Eleven samples were collected during the period between November 2013 and April 2015. To identify the origin of the thermal groundwater and for the evaluation of the reservoir temperature in the geothermal systems, the following data were used: concentrations of major chemical constituents, stable isotope ratios (δD and $\delta^{18}O$), saturation indices and chemical geothermometer temperatures. The physicochemical parameters (temperature, pH, and electric conductivity) were measured in-situ; the temperature of the thermal water samples varied from 38 to 96 °C, the pH value of these springs is slightly acid to neutral, with high electrical conductivities up to 4500 µS/Cm.

Piper diagrams highlighted two major hydrochemical facies namely sodium chloride (Na-Cl) and sodium sulfate ($Na\text{-}SO_4$). The mineral composition of the thermal waters reflects the geological formations found in the deep origin reservoir and chemical changes in the fluids were highly influenced by water-rock interaction.

The thermal waters from the study area are depleted in ^{18}O and D and plot on the global meteoric water line (GMWL), their deep-circulating meteoric origin shows that most thermal waters plot on or near the meteoric water line, with some exceptions due to Mediterranean precipitation, probable water-rock isotope exchange or mixing takes place between the ascending geothermal water and shallow colder groundwater. The subsurface reservoir temperatures were calculated using different solute geothermometers and computation of saturation indices for different solid phases. The highest estimated reservoir temperatures are indicated by the cation composition geothermometer (CCG) and the Na–K–Ca geothermometer, while slightly lower estimates are obtained using silica geothermometers, with local geothermal gradients ranging from 25 to 45 °C/km.

1. Introduction

Hot springs are any natural geothermal springs or natural discharges of groundwater with elevated temperature with respect to the surroundings (Sherpa et al., 2013). Ancient civilizations revered thermal springs because they were believed to have supernatural and healing powers (La Moreaux and Tanner, 2001). Geothermal systems need at least four parameters to be fully delineated: recharge, heat source, cap rock and the conduits for water to reach the reservoir (Kemboi, 2015).

The chemistry of thermal waters has attracted the attention of numerous researchers, in particular those investigating the influence of water-rock interactions and the large diversity of the chemical composition of fluids that are found in geothermal systems (e.g. Mahon, 1970); Tonani, 1970; White, 1970; Fournier and Truesdell, 1973; Ellis and Mahon, 1977; Fournier, 1979; Giggenbach, 1988; Pauwels et al., 1993; Tarcan and Gemici, 2003; Dib, 1985; Rezig, 1991; Issaadi, 1992; Bouchareb-Haouchine, 2012; Belhai et al., 2015; Benaabidate, 2000; Houha, 2007). Most of these studies have focused on three aspects: (1) the interaction between thermal waters and wall rock has a fundamental control on the chemical characteristics of thermal waters (e.g. Gemici et al., 2004; Cruz and França, 2006); (2) the origin of geothermal waters can be traced by using stable isotope ratios (e.g Papp and Nitoi, 2006; Boudoukha and Athamena, 2012); and (3) the reservoir can be assessed through the use of chemical geothermometry (e.g. Ahmad et al., 2002; Benaabidate, 2000).

There are more than 200 thermal springs in the Algerian territory, situated in different areas with complex geological structures (Polvêche, 1960), their number increasing regularly moving eastward. According to some geological and thermal considerations, it seems to follow that of the metalliferous ore deposits. There are about twenty hot springs in the northwestern part of Algeria, approximately 40 in that of Algérois-Hodna-Soummam basin and 150 in the northeastern part, but

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they are not all utilized. The regional geology is made up of young mountains

formed during Tertiary times by the Alpine orogeny, consisting of a number of structural-sedimentary units. (Houha, 2007).

The occurrence of thermal water is a particular phenomenon associated with the lithostratigraphic and structural conditions of its spring (Verdeil, 1982). The origin of thermal waters is complex because several parameters affect their composition, hydrothermal circulation patterns, fluid chemistry, and mineral deposition both in space and time. Isotope signatures of the hot spring waters studied provided evidence of the understanding the possible origin of these thermal waters. In addition, geochemical analysis for major ions revealed a fair assessment of the chemical nature and sub-surface reservoir temperatures of the thermal waters (Anees et al., 2015).

Hydrothermal systems can be found in various geological settings and are hosted in different types of wall-rocks (Zhu et al., 2011), but generally they are found in high heat flow and volcanic regions associated with tectonic plate boundaries, and/or in areas with sedimentary rocks of high porosity and permeability, the water in the sediments being heated by the regional heat flow (Fridleifsson and Freeston, 1994).

The paper aims to examine the hydrogeochemistry and geothermometry of thermal waters of northeastern Algeria to provide an overall assessment of: i) the origin of the thermal groundwater, ii) determine the chemical processes controlling the composition and circulation of these fluids giving rise to the salinities of these waters and iii) estimation of the subsurface reservoir temperatures characterized by the presence of many groups of thermal water. To verify this, a combination of physically based tools, hydrogeochemistry including isotope, geochemistry and conventional chemical geothermometers are used to understand the functioning of the hydrothermal system. The chemical and isotopic composition of the geothermal fluids provides information about their origin, recharge areas and flow patterns (Mutonga et al., 2010).

The ability to use thermal waters for therapeutic purposes is naturally determined by their chemical composition, Moreover, it is used for bathing (Hammam), medical treatments and in some cases for house heating, agriculture, aquaculture, bottled water and the extraction of rare elements (Petraccia et al., 2005), their energy potential (geothermal resources) (Saibi, 2009) and their socio-economic importance has fluctuated over time (Edmunds, 2004).

2. Study area

2.1. Geographical context

Our study area is located in Northeastern Algeria, bordered by the Mediterranean Sea to the north, by the Northwestern part of Algeria to the west, by The Saharan Platform to the south, and by the Tunisian border to the east (Fig. 1).

2.2. Geological and hydrological context

The geology of Algeria is divided into two main structural units: the folded Tellian Domain in the North, and the Saharan Platform in the South, separated by the South Atlasic Flexure (Fabre, 1976). The study area (Fig. 1) is delineated by the following features: the Tellian Atlas to the North, large plains in the center and the Saharan Atlas to the South and belongs to the Alpine structural domain (unstable) with significant seismic activity. It is characterized by a complex geology of overthrusting allochthonous terrains; the geological formations are mainly carbonate and marls.

The Northeastern part consists of young mountains formed during the Tertiary by the Alpine orogeny. Alpine Algeria consists of a number of structural-sedimentary units, from north to south (Askri et al., 1993):

- The Tellian Atlas is the nappe domain, with mountain basins, and a sedimentary column ranging from Jurassic to Miocene.
- The High Plateaus are the fore-land of the Alpine range bearing a thin sedimentary cover. Local distension mechanisms allowed the formation of intra-mountain basins
- The Saharan Atlas was formed from an elongated trough pinched between the High Plateaus and the Saharan Platform.

It juxtaposes two opposed hydrologic systems: Mediterranean Sea basins in the north and closed sub arid basins connected to Chotts and Sebkhas in the South (Mebarki, 2010).

2.3. Climate context

Due to its geographical position and climatic characteristics, Algeria is highly vulnerable to climate changes (Sahnoune et al., 2013). In the study area, the climate is transitional, presenting a temperate Mediterranean climate in the northern part, which includes the coast and the Tell Atlas (hot and dry summers, wet and fresh winters); semi-arid with irregular and low precipitation on a high plateau in the center and arid desert with extremely low annual precipitation beyond the Saharan Atlas. The temperatures range from over 45 °C by day to − 5 °C by night.

3. Methodology and materials

Particularly critical for thermal waters is the need to identify the source of the spring and to sample as close to the spring as possible (IAEA, 2008). The collection of samples for chemical analysis is the first step in a long process that was conducted in three stages; (a) field observation; (b) sampling and storing of the thermal spring waters in 150 ml new polyethylene bottles (for major ion analysis) and water samples for isotope determinations were stored in 50 ml high-density polyethylene bottles with small necks, capped and sealed with paraffin film, rinsed three times with sampling water then transported in a cooler.

Once arrived at the laboratory, water samples are filtered at 0.45 µm. Then, the samples are stored in the dark, in a fridge, at 4 °C, for a maximum of one week before being analyzed; and (c) analysis, data processing and interpretation of results.

The sampling locations were carefully selected according to geographical, geological and thermal considerations.

Eleven thermal water samples were collected between November 2013 and April 2015 for chemical and isotopic characterization, and were immediately brought to the laboratory in sterile conditions; all water samples were collected from locations used for bathing. At all sampling points, physicochemical parameters of the waters, such as electrical conductivity (EC), pH and temperature were measured using a portable handheld digital multi-meter. Chemical and isotope ($\delta^{18}O$ and δD) analysis was carried out at the Laboratory of Hydrogeology, University of Avignon (France). Anion species were analyzed using a Dionex Ion Chromatograph equipped with an automatic sampler with a precision better than ± 5%. Silica (SiO_2) was analyzed using colorimetric methods; Cation species were analyzed using an Atomic Absorption Spectrometer, for $\delta^{18}O$ and δD isotope analyses an isotopic ratio mass spectrometer was used

Groundwater chemical facies were determined from the Piper diagram using the computer software “Diagramme” (Simler, 2014) and AquaChem 2014.2 for ternary diagrams.

4. Results and discussion

4.1. Physicochemical parameters

The in-situ parameters are presented in Table 1. The temperatures of the thermal waters range from 38 °C measured in Hammam Garir to