Journal of South American Earth Sciences 62 (2015) 109–124

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

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

Evaluation of the solute geothermometry of thermal springs and drilled wells of La Primavera (Cerritos Colorados) geothermal field, Mexico: A geochemometrics approach

Kailasa Pandarinath [a, *], Humberto Domínguez-Domínguez [b, 1]

[a] Departamento de Sistemas Energéticos, Instituto de Energías Renovables, Universidad Nacional Autónoma de México, Priv. Xochicalco s/n., Col Centro, Apartado Postal 34, Temixco, Mor. 62580, Mexico
[b] Ingeniería en Tecnología Ambiental, Universidad Politécnica del Estado Morelos (UPEMOR), Jiutepec CP 62550, Morelos, Mexico

ARTICLE INFO

Article history:
Received 3 January 2015
Accepted 5 May 2015
Available online 14 May 2015

Keywords:
Solute geothermometers
Thermal springs
Geothermal wells
Discordant outliers
Reservoir temperature

ABSTRACT

A detailed study on the solute geothermometry of thermal water (18 springs and 8 drilled wells) of La Primavera geothermal field (LPGF) in Mexico has been carried out by employing a geochemical database compiled from the literature and by applying all the available solute geothermometers. The performance of these geothermometers in predicting the reservoir temperatures has been evaluated by applying a geochemometrics (geochemical and statistical) method. The springs of the LPGF are of bicarbonate type and the majority have attained partial-equilibrium chemical conditions and the remaining have shown non-equilibrium conditions. In the case of geothermal wells, water is dominantly of chloride-type and, among the studied eight geothermal wells, four have shown full-equilibrium chemical conditions and another four have indicated partial-equilibrium conditions. All springs of HCO_3^- type water have provided unreliable reservoir temperatures, whereas the only one available spring of SO_4^{2-} type water has provided the reservoir temperature nearer to the average BHT of the wells. Contrary to the general expected behavior, spring water of non-equilibrium and geothermal well water of partial-equilibrium chemical conditions have indicated more reliable reservoir temperatures than those of partially-equilibrated and fully-equilibrated water, respectively. Among the chemical concentration data, Li and SiO_2 of two springs, SO_4^{2-} and Mg of four springs, and HCO_3 and Na concentrations of two geothermal wells were identified as outliers and this has been reflected in very low reservoir temperatures predicted by the geothermometers associated with them (Li–Mg, Na–Li, Na–K–Mg, SiO_2 etc.). Identification of the outlier data points may be useful in differentiating the chemical characteristics, lithology and the physico-chemical and geological processes at the sample locations of the study area.

In general, the solute geothermometry of the spring waters of LPGF indicated a dominantly (94%) of underestimated deep reservoir temperatures, whereas in the case of the geothermal wells, many temperatures (54%) are underestimated, some are (43%) overestimated and a very small number (3%) are similar to an average bottom-hole temperatures (BHT) of the wells. 28 out of the total applied 29 geothermometers for spring waters have predicted the deep reservoir temperatures that are characterized by statistically significant large differences compared to the average BHTs of the geothermal wells. In the case of waters of the geothermal wells, 23 out of the total applied 28 geothermometers have predicted the reservoir temperatures similar (statistically no significant differences) to the BHTs of the corresponding geothermal wells.

1. Introduction

Geothermometers are valuable tools during the exploration (in the evaluation of new fields) and exploitation (in monitoring the hydrology of the existing geothermal systems) stages of the production of geothermal energy. Solute geothermometers are widely

---

[*] Corresponding author. Tel.: +52 55 56229773; fax: +52 55 56229791.
E-mail address: pk@ier.unam.mx (K. Pandarinath).

[1] Was on an academic stay at IER-UNAM, during 2012–2013, for realizing the undergraduate thesis work.

http://dx.doi.org/10.1016/j.jsames.2015.05.002
0895-9811/© 2015 Elsevier Ltd. All rights reserved.

applied for geothermal water derived from thermal springs (Güileç, 1994; Simmons et al., 1994; Quinto et al., 1995; Nieva et al., 1997; Ahmed et al., 2002; Lambrakis and Kallergis, 2005; Allen et al., 2006; Dotsika et al., 2006; Verma et al., 2006; Siebe et al., 2007; Pandarinath, 2011) and from drilled geothermal wells (Kruger et al., 1985; Güileç, 1994; Portugal et al., 2000; Verma, 2002; González-Partida et al., 2003, 2005; Verma et al., 2006; Díaz-González et al., 2008; Palabiyik and Serpen, 2008; Pandarinath, 2011; García-López et al., 2014) in the estimation of reservoir temperatures. Up to date, there are 35 geothermometric equations for solute geothermometers involving different chemical elements such as Na–K (Fournier and Truesdell, 1973; Truesdell, 1976; Fournier, 1979; Tonani, 1980; Arnórsson et al., 1983; Giggenbach, 1988; Verma and Santoyo, 1997; Arnórsson, 2000; Can, 2002; Díaz-González et al., 2008), K–Mg (Giggenbach, 1988; Fournier, 1991), Li–Mg (Kharaka and Mariner, 1989), Na–Li (Fouillac and Michard, 1981; Kharaka and Mariner, 1989; Verma and Santoyo, 1997), Na–K–Ca (Fournier and Truesdell, 1973; Nieva and Nieva, 1987; Kharaka and Mariner, 1989), Na–K–Ca–Mg (Nieva and Nieva, 1987), cationic composition geothermometer (CCG, Nieva and Nieva, 1987), and SiO_2 (Fournier, 1977; Fournier and Potter, 1982; Verma and Santoyo, 1997; Arnórsson, 2000; Verma, 2000), which were successfully applied for estimating the reservoir temperature of various geothermal systems.

Currently, there are four important geothermal fields in Mexico (Cerro Prieto, Baja California; Las Tres Vírgenes, Baja California Sur; Los Azufres, Michocán; and Los Humeros, Puebla) which are being used for production of electricity with a total installed capacity of 958 MWe (Gutiérrez-Negrín et al., 2010). Another geothermal field, La Primavera, also known as Cerritos Colorados, is also promising for production of electricity with an assessed potential of 75 MWe (measured bottom-hole temperatures, BHTs, >300 °C; Dominguez and Lippmann., 1983). However, during the production, BHTs were dropped and the fluid chemistry has changed which has been attributed to inadequate well completions. Nevertheless, detailed investigations have indicated that a good geothermal prospect might exist below 3000 m depth (Dominguez and Lippmann, 1983).

There are some studies on the geothermometry of the thermal springs and wells of this geothermal field. Mahood et al. (1983) have estimated the subsurface temperatures that ranged between 148 and 199 °C by applying Na–K geothermometer of Fournier (1979), and from 93 to 163 °C by Na–K–Ca geothermometers of Fournier and Truesdell (1973) and Fournier and Potter (1979) from seven springs. Kruger et al. (1987) have estimated the temperatures that ranged between 223 and 297 °C and between 237 and 295 °C, respectively, by applying Na–K–Ca geothermometer of Fournier and Truesdell (1973) and SiO_2 geothermometer of Fournier and Potter (1982) for thermal waters of five drilled geothermal wells (PR-1, PR-2, PR-5, PR-8, and PR-9). Verma et al. (2012) have obtained the reservoir temperatures that ranged between 99 and 202 °C for springs and between 131 and 298 °C for wells by applying only those solute geothermometers which are equipped with estimations for errors (4 Na–K geothermometers of Fournier, 1979; Verma and Santoyo, 1997, and Díaz-González et al., 2008; two Na–Li geothermometers of Fouillac and Michard, 1981; Verma and Santoyo, 1997; and two quartz geothermometers of Fournier and Potter, 1982, and Verma and Santoyo, 1997).

Pandarinath (2011) has reported that not all springs nor all solute geothermometers provide reliable estimations of the reservoir temperatures. Grouping of thermal springs based on a suitable geochemical classification of water types, and outlier-free chemical data has demonstrated some better temperature ranges for Los Azufres (LAGF) and Las Tres Virgenes (LTVGF) geothermal fields. Similarly, García-López et al. (2014) have evaluated the effectiveness of solute and gas geothermometers based on a geochemometrics study to predict deep reservoir temperatures of ten geothermal systems. Such study reports a high prediction performance for Na/K geothermometers in the majority of liquid-dominated reservoirs and low prediction performances for the vapor-dominated and high temperature reservoirs. This paper undertakes a similar study, with regard to the effectiveness of the solute geothermometers in predicting the reservoir temperatures for the La Primavera geothermal field.

2. Geology of the study area

La Primavera geothermal field (LPGF) is situated (103°28′–103°43′ W and 20°32′–20°43′ N; Fig. 1; about 20 km west of the city of Guadalajara, Jalisco) in the western part of the Mexican Volcanic Belt (MVB), near to the intersection of three regional structures (Colima graben with north-south orientation, Chapala graben with east-west direction, and Tepic-Chapala graben with northwest-southeast direction; Gutiérrez-Negrín, 1988). The geothermal field is located in a rhyolitic volcanic complex (Mahood, 1980) whose formation has began around 120, 000 years ago, when a regional uplift produced two curved fracture zones through which first rhyolitic flows and domes were erupted (Gutiérrez-Negrín, 1988). Studies on core cuttings from these wells revealed that the wells cut lacustrine sediments, ignimbrites produced by calderic eruptions, a sequence of andesites and pyroclastic rocks (lithic tuffs) with thin intercalations of rhyolites (Gutiérrez-Negrín, 1988). Drilling of wells has revealed that the geology of the area could be subdivided into four lithological units: (1) the oldest unit consists of granitic and granodioritic rocks; (2) an andesitic layer, overlies this granitic basement unit; (3) rhyolites; and (4) the upper basement unit is a sequence of lithic tufts and minor andesites (Gutiérrez-Negrín, 1988). The detailed geology of the La Primavera caldera has been reported by Mahood (1977 and 1980), Mahood et al., (1983) and Verma and Rodríguez-González (1997).

The oldest eruption took place around 120 ka ago followed by another eruption at 95 ka that created the lithic tuffs (Tala tuff). This eruption caused the collapse of the magmatic chamber and the formation of an 11-km diameter caldera surrounded by rhyolitic domes (Vega-Márquez et al., 2001). Volcanic activity resumed at 20 ka with the eruption of rhyolitic domes. The caldera collapse developed local faults striking NW–SE and NE–SW and surface manifestations (fumaroles and thermal springs) are located along these faults. After the dome eruption, a hydrothermal system was developed (Mahood et al., 1983; Gutiérrez-Negrín, 1991). The temperature field distribution in LPGF with simulation in two dimensions (2-D; Verma and Rodríguez-González, 1997) and in three dimensions (3-D; Verma et al., 2012) were studied from cooling of a shallow magma chamber.

Up to now, 13 wells were drilled in this geothermal field (Flores-Armenta and Gutiérrez-Negrín, 2011) with well depths ranging from 668 (PR-4, shallowest) to 2, 986 m (PR-9, deepest) and the measured stabilized temperatures vary between 90 (well PR-4) to 348 °C (well PR-9) (Gutiérrez-Negrín, 1988).

3. Methodology

We have prepared an integrated database by compiling water chemical composition data of the thermal springs and drilled geothermal wells from the literature (Domínguez-Domínguez, 2013). For this purpose, the thermal springs and geothermal wells which contain the concentration data of cations and anions as wells as bottom well temperatures are only considered. Based on this condition, we could obtain the required chemical data for 18 thermal springs and 8 drilled geothermal wells of LPGF (Table 1). Water chemical data of springs is compiled from Mahood et al.