Journal of Volcanology and Geothermal Research xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

Evaluation of mineral-aqueous chemical equilibria of felsic reservoirs with low-medium temperature: A comparative study in Yangbajing geothermal field and Guangdong geothermal fields

Jiexiang Li [a], Gideon Sagoe [a], Guang Yang [a], Guoping Lu [b,*]

[a] School of Environmental Studies, China University of Geosciences, Wuhan 430074, China
[b] Institute of Groundwater and Earth Sciences, Jinan University, Guangzhou 510632, China

ARTICLE INFO

Article history:
Received 15 May 2017
Received in revised form 29 November 2017
Accepted 12 January 2018
Available online xxxx

Keywords:
Low-medium temperature reservoir
Magma
FixAl method
Classical geothermometers

ABSTRACT

Classical geothermometers are useful tools for estimating reservoir temperatures of geothermal systems. However, their application to low-medium temperature reservoirs is limited because large variations of temperatures calculated by different classical geothermometers are usually observed. In order to help choose the most appropriate classical geothermometer for calculating the temperatures of low-medium temperature reservoirs, this study evaluated the mineral-aqueous equilibria of typical low-medium temperature felsic reservoirs in the Yangbajing geothermal field and Guangdong geothermal fields. The findings of this study support that reservoirs in the Guangdong geothermal fields have no direct magma influence. Also, natural reservoirs may represent the intermediate steady state before reaching full equilibrium, which rarely occurs. For the low-medium temperature geothermal systems without the influence of magma, even with seawater intrusion, the process of minerals reaching mineral-aqueous equilibrium is sequential: chlorite and chalcedony are the first, then followed by K-feldspar, kaolinite and K-mica. Chlorite may reach equilibrium at varying activity values, and the equilibrium between K-feldspar and kaolinite or K-feldspar and K-mica can fix the contents of K and Al in the solutions. Although the SiO_2 and Al attain equilibrium state, albite and laumontite remain unsaturated and thus may affect low-medium temperature calculations. In this study, the chalcedony geothermometer was found to be the most suitable geothermometer for low-medium temperature reservoirs. The results of K-Mg geothermometer may be useful to complement that of the chalcedony geothermometer in low-medium temperature reservoir systems. Na-K geothermometer will give unreliable results at low-medium temperatures; and Na-K-Ca will also be unsuitable to calculate reservoir temperatures lower than 180 °C, probably caused by the chemical imbalance of laumontite.

1. Introduction

In hydrothermal systems, geothermometers are the most common tools usually employed to estimate the temperature of reservoirs because they are more convenient apart from their efficiency. However, the successful application of the classical geothermometers relies on the following basic assumptions (Nicholson, 1993). Firstly, the concentration of the elements or species used in the geothermometer is only controlled by a temperature-dependent mineral-fluid reaction. Based on the water-rock ratio, geothermal systems can be divided into rock-dominated hydrothermal alteration systems and fluid-dominated hydrothermal alteration systems. In fluid-dominated hydrothermal alteration systems, to some extent, the metasomatism, like H-metasomatism at the margins of upflow zones, K-alteration and silicification in the major upflow zones, and propylitic alteration in the recharge zones can disturb the equilibrium state of minerals in the geothermal reservoirs. What is more, partial or no equilibrium of temperature-dependent mineral-fluid reaction can also bring about inaccurate estimation of reservoir temperatures. Secondly, the rock-fluid system is assumed to be rich in the minerals and dissolved species involved in the reactions related to the geothermometer to be applied, for equilibrium in the reservoirs to be attained. The host rock of a reservoir is therefore a key factor for the correct application of classical geothermometers. Another assumption is that the fluids leave the reservoirs ascending to the surface with no re-equilibration, including no near-surface reactions. Slow ascent of geothermal fluid will allow enough time for heat transfer and reactions between the fluids and the surrounding rocks. Consequently, the composition and concentrations of species in the solutions may change, and hence pose a difficulty in ascertaining the original composition and species concentrations in the solutions. However, when the geothermal fluids ascend to the

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* Corresponding author.
E-mail address: guopinglu@jnu.edu.cn (G. Lu).

https://doi.org/10.1016/j.jvolgeores.2018.01.008
0377-0273/© 2017 Published by Elsevier B.V.

Please cite this article as: Li, J., et al., Evaluation of mineral-aqueous chemical equilibria of felsic reservoirs with low-medium temperature: A comparative study in Yangbaj..., J. Volcanol. Geotherm. Res. (2017), https://doi.org/10.1016/j.jvolgeores.2018.01.008

surface quickly due to reduced hydraulic pressure by boiling, and cooling is achieved through approximate adiabatic process, steam formation causes increase in the concentration of species in the fluids such that the re-equilibration of mineral-fluid reaction may still occur. Additionally, geothermal fluids might be mixed with other types of waters before discharge, which will also change the hydrochemical environment and further influence the species in the solutions. Therefore, employing classical geothermometers to evaluate reservoir temperature must be done with caution since application of all geothermometers will not be equally valid for all hot springs, as different thermal springs have varying characteristics and conditions.

For low-medium temperature (<180 °C) reservoirs, the calculated results of geothermometers show significant variations. For example, on a global scale, Na-K geothermometer always performs well for the reservoirs with temperatures ranging from 180 to 350 °C (Ellis, 1979), but fails at lower temperatures, especially at <120 °C (Nicholson, 1993). The Na-K-Ca geothermometer also gave reliable results when applied to waters from high temperature reservoirs (>l80 °C), but failed at lower temperatures (Nicholson, 1993). These experiential conclusions on geothermometers possibly suggest that the state of mineral-aqueous chemical equilibrium in low-medium temperature reservoirs differs from the high temperature reservoirs. In high temperature geothermal fields like the Tengchong geothermal field and Kangding geothermal field in China, Na-K geothermometer gave logical calculated temperatures of higher temperature reservoirs, yet K-Mg geothermometer failed (Guo and Wang, 2012; Li et al., 2015; Guo et al., 2017). However, for low-mid temperature geothermal fields, located in the west coastal area of Guangdong Province, where reservoir temperatures are about 150 °C, the calculated results of Na-K geothermometer and Na-K-Ca geothermometer are abnormally high (Guo et al., 2016).

Nevertheless, the understanding of mineral-aqueous chemical equilibrium of felsic reservoirs with low-medium temperature is not enough, and various researchers have proposed their own viewpoints. Mineral-aqueous chemical equilibrium in moderate temperature geothermal reservoirs is probably universal, and that degassing, dilution, or errors in water analysis may cause apparent departures from such equilibrium (Pang and Reed, 1998). In the Iceland geothermal fields, Na^+ and K^+ activity ratio of geothermal waters with temperature as low as 50 °C, closely approaches that predicted from thermodynamic data for the reaction between low-albite and microcline (Stefánsson and Arnórsson, 2000). However, in natural geothermal reservoirs, the solute contents are likely to represent the intermediate steady state, which depends on the rates of dissolution of primary minerals and disposition of secondary phases (Giggenbach, 1984). In terms of K-feldspar and albite, reservoirs can be close to or even reach equilibrium in geothermal systems if the temperature higher than 200 °C (Giggenbach, 1988; Stefánsson and Arnórsson, 2000), but the extent of water-mineral interactions of low-medium temperature (<200 °C) reservoirs may vary. Recent studies on carbonate-evaporitic thermal systems with lower reservoir temperatures (about 100 °C) have also shown that albite and K-feldspar can always attain equilibrium due to the presence of detrital rocks (Blasco et al., 2017; Blasco et al., 2018). The conclusions above demonstrate that mineral-aqueous chemical equilibrium is not consistent for all cases. Therefore, before using classical geothermometers to calculate the temperature of low-medium temperature reservoirs, the assumption that water-mineral equilibrium is established cannot be justified, and may lead to unpredictable errors. For a more proper application of classical geothermometers in low-medium temperature reservoirs, the determination of the state of water-mineral interactions related to different kinds of classical geothermometers is thus imperative. In low-medium temperature reservoirs, there exists a common reaction sequence of different kinds of minerals. The aim of this study was therefore to identify the most possible minerals which equilibrate with geothermal water in low-medium temperature reservoirs. This will help increase reliability of temperature estimation of low-medium temperature reservoirs when using classical geothermometers.

The Guangdong geothermal fields are typical coastal geothermal systems, located in southeast coast of China (Lu et al., 2017; Lu and Liu, 2015). The heat source in these fields has not been confirmed yet. The Yangbajing geothermal field is one of the famous geothermal fields in Tibet, China, where much research work has been done. The existence of magmatic heat source has been confirmed at Yangbajing using various approaches (Brown et al., 1996; Kind et al., 1996; Nelson et al., 1996). Quite interestingly, these two areas have some similarities that allow a comparative study: 1) the depth of molten granite, about 15–25 km in Yangbajing geothermal field, is close to the depth of the low resistivity zone, about 20 km, beneath one of the Guangdong geothermal fields, Xinzhou geothermal field; and 2) the reservoirs have similar lithology, as both are dominated by granite. Hence, a comparative study of the two fields will be meaningful to confirm whether or not, the Xinzhou geothermal field is directly influenced by magma. Furthermore, the Xinzhou geothermal field has high concentration of Cl, which may be as a result of seawater intrusion. Therefore, the Guangdong geothermal fields can also be studied on the influence of seawater intrusion on the mineral-aqueous chemical equilibria in such reservoirs.

2. Geological and hydrogeological settings

In Guangdong Province, there is a wide distribution of faults, and the main faults have the E–W, NE–SW, and NW–SE directions. Most of the faults with the E–W direction have depths > 30 km (Lu and Liu, 2015). The depth of NE–SW direction faults can extend to 20 km underground, and many geothermal springs scatter along the NE–SW direction faults. This suggests that the NE direction faults may be the main channels to transmit the geothermal energy from the deeper depths to the surface of the earth. The NW–SE direction faults are shallower, with the depth < 20 km, with most being about 10 km deep.

In the Fengshun geothermal field, there is wide distribution of Mesozoic granite, and the lithology of the geothermal reservoirs is granite (Zhou and Yang, 1992). In Xinzhou, sandstone, shale, Quaternary deposits and Yanshanian granite are exposed (Zhou, 1986). The composition of the reservoir lithology is Yanshanian biotite-granite (Chen, 1990). Also in the Xinzhou geothermal field, is a large area of low resistivity zone at the depth of about 20 km (Lin et al., 2016). Near the E–W fault, as shown in Fig. 1, is a tensional fault which acts as the main flow path for the underground hot water (Tian, 2016). For the Xinyi geothermal field, granite is the most common outcrop in the area, which means that the lithology of the geothermal reservoirs is also likely to be granite. All the geothermal fields in Guangdong show significant seasonal variations in outflows and aqueous compositions (Wang et al., 2018; Lu et al., 2017; Lu and Liu, 2015).

The Yangbajing geothermal field, located in the Yangbajing fault basin, is one of the non-volcanic high temperature fields in Tibet. This geothermal system consists of two reservoirs at different depths: the shallow reservoir is at a depth of 180–280 m, and the deep reservoir at 950–1850 m (Duo, 2003). The shallow reservoir consists of weathered granite and Quaternary sandstones in the north and Quaternary sediments in the south. Contrastingly, granitic mylonite and fractured granite constitute the deep reservoir (Guo et al., 2007). The temperature of the shallow reservoirs ranges from 130 °C to 173 °C, whilst that of the deep reservoirs is from 240 to 329.8 °C (Guo et al., 2007). Molten granite at a depth of 15–25 km, with a thickness of 20 km is the heat resource of Yangbajing geothermal field (Zhao et al., 1998).

3. Methods

3.1. Sample collection and laboratory analysis

In the Guangdong geothermal fields, a total of 25 samples were collected in July 2016, including 20 geothermal waters and 5 local cold

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