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Major hydrogeochemical processes controlling the composition of geothermal waters in the Kangding geothermal field, western Sichuan Province

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ABSTRACT

The Kangding geothermal field, located in western China, is a high-temperature geothermal system potentially rich in geothermal resources. In this study, we employed various hydrogeochemical methods to gain more insight into the heat source and cooling processes involved in forming various thermal springs in the geothermal field. The study showed that though the majority of the samples analyzed were immature in terms of mineral-aqueous equilibria, coupling classical geothermometers with the FixAl method enabled more reliable reservoir temperature estimations. A deduction from the silica-carbonate, the chloride-enthalpy, and the silica-enthalpy mixing models indicated that the parent geothermal fluid exists beneath this study area. The thermal waters discharged from the Kangding geothermal field originate in the same deep reservoir; and the parent geothermal fluid has a temperature of about 260 °C, with a Cl^- concentration of 1056 mg/L. Isotope (δD and $\delta^{18}O$) studies confirmed the magmatic heat effect on the parent geothermal fluid. Also, though all the thermal spring waters in the field are derived from the parent fluid, they undergo different cooling processes during ascent to the earth's surface. However, the thermal spring waters in both the Yulingong and Erdaoqiao geothermal sites were mainly formed by the mixing of the parent geothermal fluid and infiltrating groundwater. The thermal spring waters in the Erdaoqiao also had the highest levels of Ca^{2+}, Mg^{2+} and TIC (total inorganic carbon) due to the presence of carbonate in its geologic stratum. The thermal springs at Zhonggu formed as a result of the "CO_2 condensate", consisting of snow-melt water and meteoric water, mixing with the deep parent geothermal fluid. We attribute the absence of acid springs in the Kangding geothermal setting to the deep-seated magma chamber and a relatively small concentration of H_2S in the deep thermal waters in the area.

1. Introduction

In geothermal systems with a magmatic heat source, the primary neutralization fluids in the deep reservoirs are of the type Cl-Na-K, and their Mg and Ca concentrations are low due to the formation of Mg-rich and Ca-rich alteration products (Giggenbach, 1988). During the ascent of geothermal fluid to the surface from deep reservoirs K-alteration and minor H-alteration, due to secondary neutralization of CO_2, are the major processes that affect the chemical composition of the fluid (Giggenbach, 1988). At this stage, the hydrochemical type of geothermal fluid is basically Cl-Na, which is also called "parent geothermal fluid." A full equilibrium state of the water-mineral reaction in the parent geothermal fluid usually indicates that the geothermal fluid is influenced by magma.

The high-temperature geothermal systems, in China, are mainly located in the Yunnan Province, Tibet and the western Sichuan Province (Liao and Zhao, 1999). The high-temperature hydrothermal activity area of western Sichuan is located in the eastern Mediterranean-Himalayan geothermal activity zone, and the Kangding geothermal field is a high-temperature geothermal system and is a part of the hydrothermal activity area of western Sichuan (Guo et al., 2017). The geochemical characteristics of the Kangding geothermal field are similar to those of the high-temperature geothermal resources of Yangbajain and Yangyi geothermal fields in Tibet (Chen et al., 2015). Therefore, the Kangding geothermal field deserves more attention as it may be rich in geothermal resources. The springs in the northern-middle section of the Kangding geothermal field are located in the valley of the Yala River, and the observed temperatures are 54–74 °C, which are relatively low. However, in the southern section (Yulingong region) the springs are located along the Yuling river, and the springs generally have high temperatures. According to a statistical estimation by Tong and Zhang (1994), the highest temperature of a hot spring in

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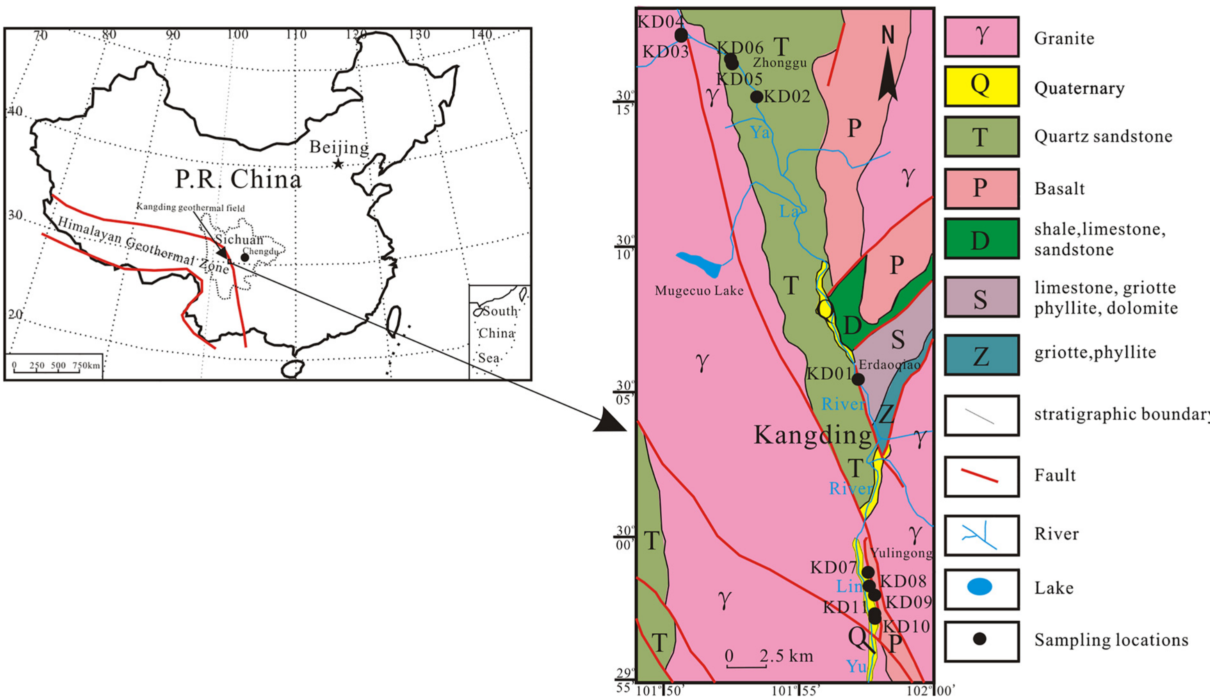

Fig. 1. Simplified geological map of the study areas and sampling locations.

Yulingong is 87.5 °C, but the Zhang et al. (2017) obtained temperatures for the Yulingong group springs up to 89–91 °C, which is beyond the local boiling point; and the wellhead temperature of the geothermal well in this area has reached 178 °C. Recently, Guo et al. (2017) calculated the temperature of the reservoirs beneath Yulingong and found reservoir temperatures ranging from 250 to 280 °C. Though Guo and others explained the formation processes of the different springs in Yulingong, the specific cooling processes that the springs undergo, and the heat source in the Kangding geothermal field were not adequately described. Besides, Chen et al. (2015) obtained reservoir temperatures in the Kangding geothermal field by silica and K-Mg geothermometers without analyzing the hydrogeochemical processes of the springs. Based on geophysical data and the hydrogeochemical characteristics of thermal waters in the Kangding geothermal field, Zhao (1984) inferred that magma exists beneath this area. However, direct evidence that supports the existence of magma, which consequently influences the components of geothermal fluids is inadequate. Moreover, whether the parent geothermal fluid exists in Kangding geothermal field is still unknown. What is more, the application of hydrogeochemical methods to study the origins of the springs in the Kangding geothermal field has not been sufficient.

It is well known that all classical geothermometers have their own application limitations, and so using them indiscriminately to estimate reservoir temperatures may generate large deviations from the true values (Fournier and Truesdell, 1973). Besides, it is difficult to use classical geothermometers only to reliably calculate the temperature of deep geothermal fluids, like parent geothermal fluids, unless supported by mixing models. However, using mixing models such as the chloride-enthalpy mixing model (Fournier, 1979), the silica-enthalpy mixing model (Fournier and Truesdell, 1974), and the silica-carbonate mixing model (Arnórsson, 1985) may give varying results. Therefore, in this study, both classical geothermometers and the FixAl method were first used to calculate relatively accurate reservoir temperatures. Then by plotting different mixing models, the cooling processes for the various springs in the Kangding geothermal field were determined. We also investigated the possible existence of the parent geothermal fluid beneath the Kangding geothermal field. Analysis of deuterium and oxygen isotope ratios was conducted to verify the results on the existence or absence of magma influence in the thermal field.

2. Geothermal and geological setting

Kangding is in the front part of the collision area of the Indian Plate with the Eurasian Plate, and has a complicated tectonic deformation (Xuan et al., 2015). Based on the results of the INDEPTH project, it is evident that from the results of the deep seismic profiling across the Main Himalayan Zone, the footwall of the thrust zone has been subducted northwards over more than 200 km, reaching a depth of 15 km (Liao, 2018). Additionally, many deep reflection highlights were found at the depth of 15 km, which could belong to the crust remelting type of a magma source region; and the pear-shaped shallow high-conductor at a depth of more than 10 km could be the molten or semi-molten state magma chamber of a late tectonic intrusion (Liao, 2018). According to a field survey and observations in western Sichuan Province, the local geologic structures have an effect on water and heat activity, and the hot springs are primarily exposed in the active tectonic fault zones and valleys (Zhang et al., 2017). The Kangding hydrothermal system is controlled by the Xianshuihe fault, which is a modern active fault. It cuts deep into the crust, building pathways for hydrothermal activity, and offering the tectonic foundation for the hydrothermal system. There have been three periods of magmatic activity in the Xianshuihe fault belt, and as a result, in the Kangding region there is a large granitic pluton, the Gangangshan-Zheduoshan Pluton, which intruded parallel to the fault along the Xianshuihe fault belt (Zhang et al., 2017). The intrusive rock is 80–90 km long and 7–20 km wide, and is the product of a magmatic intrusion with contemporaneous sheering of the Xianshuihe fault (Zhang et al., 2017). The Kangding geothermal field is located in the southeastern part of Xianshuihe fault, which is called the Kangding-Shimian fault-zone. In this zone, the rocks are mainly Proterozoic granite, Palaeozoic strata and some Quaternary sediments in the intermountainous basins (Du et al., 2006).

Bounded roughly by the River Yala and the River Yulin, the western lithology is primarily Xikang Group metamorphic rocks and Indosinian-Yanshanian period granite, whilst the lithology of the eastern part is Permian basalt and Jinning period intrusive quartz diorite, as shown in Fig. 1. The hot springs in the Kangding geothermal field, are linearly