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Geothermal fluid circulation in the Guide Basin of the northeastern Tibetan Plateau: Isotopic analysis and numerical modeling

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ABSTRACT

The Zhacang geothermal field in the Guide Basin, in the northeast of the Tibetan Plateau, is considered a potential target for establishing a geothermal power plant. This study investigated the formation mechanisms of geothermal resources in this field by combining isotopic analysis (^{3}H, D, ^{18}O, ^{3}He and ^{4}He) and numerical modeling of fluid-heat-helium transport. δD and δ^{18}O indicated that the meteoric water is the most likely source of the geothermal water in the Zhacang field, with depleted δD and δ^{18}O in deeper water indicative of recharge via snow melt and/or from cooler climates. A west-east trending conductive fault acts as a conduit that transports this meteoric water from an overlying stream and the Quaternary aquifer to the fractured granites in the Zhacang field. The downward groundwater movement in this conductive fault is driven by gravity force, and water temperature increases with depth. An uneven temperature distribution induces buoyancy force which results in heated water being transported upward to the land surface at positions where the conductive fault intersects an impermeable north-south trending fault. The water mass balance between recharge and discharge rates and the numerical modeling of the helium ratio imply that there is no external fluid input from the deep subsurface to induce the abnormally high temperature in the Zhacang field. Instead, the heat is generated by the friction of fault activity and/or the remaining heat in granite formed in the Triassic. The numerical modeling of heat and flow transport yields a circumfluence flow pattern in the fault zone, where a stagnant flow zone with high groundwater residence time appears. Both flow velocity and temperature distribute unevenly in the fault and never reach a steady state under the joint influence of gravity force and buoyancy force.

1. Introduction

Collision between the Indian subcontinent and Asian continent leads to crustal thickening, creating the Tibetan Plateau. The lithosphere in the Tibetan Plateau reaches its maximum depth in the south, and thins abruptly toward the center. The thickness of the crust increases again toward the northeast (Jiménez-Munt et al., 2008) (Fig. 1). The changes in the crustal thickness cause heat flow to vary significantly in the Tibetan plateau. However, widespread geothermal activities indicate that the Tibetan Plateau is abnormally hot (Brown et al., 1996).

The greatest heat flow on the Tibetan Plateau occurs in the middle zone (typically northern Lhasa and Qiangtang terrain), where the heat flow is estimated at 80–90 mW/m^2 (Hu et al., 2000). In this region there are many well-known thermal fields, such as the Rehai and Yangbajing fields. Geothermal energy has been utilized to generate electrical power at these sites (Bai et al., 2001; Du, 2005; Zeng et al., 2014). Heat flow decreases to roughly 40–50 mW/m^2 in the northeastern Tibetan Plateau (Hu et al., 2000). In this region, layered thermal reservoirs were identified in the Xining and Gonghe Basins (Tan et al., 2012), where the maximum temperature observed at a depth of 3000 m exceeds 200 °C.

The Guide Basin locates between the Xining and Gonghe Basins. An outflow temperature of 80 °C was observed in an artesian well with a drilling depth < 200 m. This attracted geothermal exploration in this basin. Since 2000, the drilling campaign has completed three drillholes with depths exceeding 1000 m. These drillholes reveal a sequence of thermal water-bearing formations composed of sandstone and siltstone, underlain by the hot dry granite rocks. The in-situ temperature measured in the thermal water-bearing formations ranges from 40 °C to 90 °C, while at the depth of 3000 m the average temperature in the hot dry rock reaches 150 °C. The existing geothermal water in the geothermal reservoir has a low-to-median temperature, with large quantities of energy stored in the hot dry rocks. Given these characteristics,

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Nomenclature

α	Thermal dispersivity, m
β	Thermal expansion coefficient, 1/°C
$\rho_f c_f$	Heat capacity of fluid, J/m^3 °C
$\rho_r c_r$	Heat capacity of solid, J/m^3 °C
D	Diffusion coefficient, m^2/d
Δx	Size of each element, m
f_μ	Constitutive viscosity relation function
h	Hydraulic head, m
K	Hydraulic conductivity, m/d
λ_b	Bulk thermal conductivity, W/m°C
λ_f	Thermal conductivity for fluid, W/m°C
λ_s	Thermal conductivity for solid, W/m°C
ϕ	Porosity
P	Production rate of helium, g/m^3/d
q	Darcy flux, m/d
ρ_{f_0}	Reference fluid density at 10 °C, kg/m^3
ρ_f	Fluid density, kg/m^3
ρ_r	Solid density, kg/m^3
S	Specific storage, 1/m
t	Time, day
T	Temperature,°C
T_0	Reference temperature, 10 °C
x	Horizontal coordinate, m
z	Vertical coordinate, m

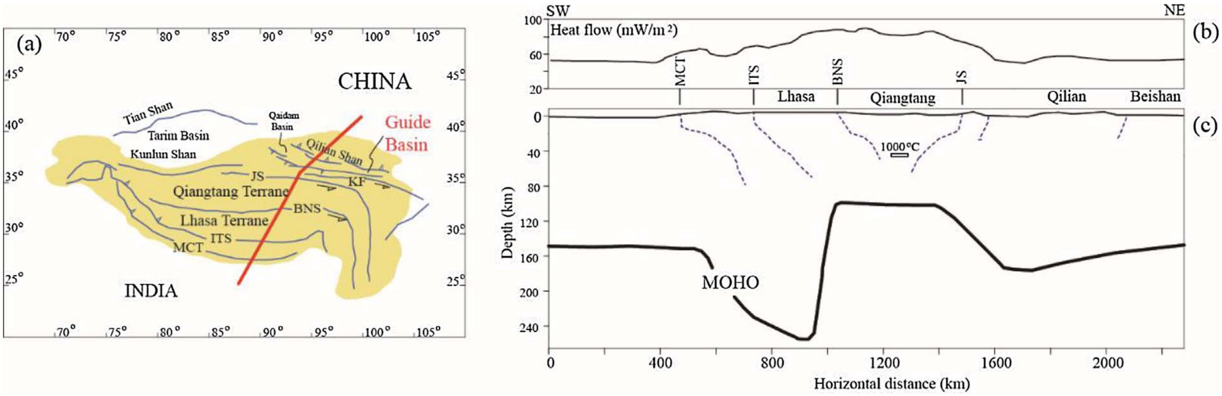

Fig. 1. (a) Tectonic map of the Tibetan Plateau with the red line showing the position of the crust profile, (b) surface heat flow along the crust profile and (c) the thickness of the crust. Modified from Jiménez-Munt et al. (2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Guide Basin has potential to provide geothermal power.

However, hydrogeological investigations regarding the thermal activities in the Guide Basin are lacking. A recent isotope study in a neighboring basin on the northeast margin of the Tibetan Plateau, the Xining Basin, concluded that geothermal water is primarily sourced from meteoric water, with a minor portion mixing with crustal magmatic fluid. Radiogenic heat and fault friction are regarded as the heat source in the Xining basin (Tan et al., 2012). However, it is unknown if the thermal processes in the Guide Basin are comparable to that in the Xining Basin.

This study focuses on the most typical geothermal field in the Guide Basin, the Zhacang geothermal field, and aims to understand flow and heat transport processes associated with the formation of high-temperature springs and wells in this field. Following the review of geological condition in the Zhacang geothermal field and our field investigations in Section 2, multiple isotopic analyses are employed to establish a conceptual model that describes the source and transport processes of water and heat in Section 3. Based on this conceptual model, a numerical model for coupled flow-heat-helium transport is constructed in Section 4. The model is validated against the temperature logs and helium ratio observed in the geothermal well in Section 5, and the validated model is used to quantitatively reproduce the geothermal processes in the Zhacang geothermal filed. The results provide additional insight into the geothermal processes in the Tibetan Plateau.

2. Background

2.1. Geologic and hydrological settings

The Guide basin is an intramontane basin that formed in the Cenozoic, and has an area of 1135 km^2. It lies across the west Qinling thrust belt (Liu et al., 2007), and is bonded to the north by Laji Mountain, to the west by Waligong Mountain, and to the south by eastern Kunlun Mountain (Fig. 2a). The basin basement consists of the Triassic clastic rocks and granites (partly fractured). In the Cenozoic, sediments from the Laji Mountain and the northern Qinling thrust belts were transported and deposited in the alternating lacustrine and alluvial environments, creating the major stratigraphy in the Guide Basin (Fang et al., 2005; Liu et al., 2007). These strata are composed of sandstone, conglomerate, siltstone and mudstone. According to the lithology, the strata are divided into two aquifers (HG and XGG aquifers) separated by two aquitards (Amigang and Ashigong aquitards), which are overlain by the Quaternary aquifer (Fig. 2c). However, the tectonic activities in the Cenozoic resulted in the uplift of the granite basement, and subsequently, the discontinuous distribution of aquifers and aquitards (Fig. 2b).

The outflow temperatures of the springs show that the average temperature in the deeper XGG aquifer is higher than 50 °C, while in the shallower HG aquifer the average temperature is 41 °C. In the Zhacang geothermal field, a thermal spring (RS11) has a temperature of 67.2 °C and a shallow artesian well (RS7, < 200 m) has an outflow temperature of 80 °C (Fig. 2a and b). The total flow rate from the artesian well and thermal spring is roughly 210 m^3/d. In order to understand geothermal processes in the Zhacang field, a deep well (ZR1) was drilled in 2010 to a depth of 3000 m, which obtained a well-head temperature of 90.2 °C and the bottom temperature of 150 °C (Fig. 3).

The stabilized temperature in ZR1 generally increases with the depth, with two decreases at depths of 200 m and 1200 m, respectively, due to the lithology heterogeneity (Fig. 3). The average temperature gradient from 500 to 2500 m is 1.3 °C per 100 m, due to the cool water input via the permeable sandstones, while at the depth > 2500 m the gradient in the granite becomes 3 °C per 100 m. The gradient in the