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Geologic Setting of the Potential EGS Site at the Gonghe Basin, China: Suitability for Research and Demonstration of Hot Dry Rock Geothermal Energy Development

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ABSTRACT

Hot dry rocks (HDR) are increasingly explored now in China, and the Gonghe Basin in the northeastern edge of the Qinghai-Tibetan Plateau is regarded as the first potential demonstration site to exploit the HDR geothermal energy. Four wells were drilled in the Gonghe Basin, which revealed a highest temperature of 236°C at the depth of 3705 m. Downhole temperature logs indicated that the geothermal gradient in the hot granite is 71.4°C/km, with a mean heat flow of 119.3 mW/m^2. Seismic, magnetotelluric and electrical prospecting in the Gonghe Basin indicated that heat transport from the magma chamber in the depth of 8 to 32 km to the shallow zones via the NW-SE striking faults within the depth of 15 to 35 km. The geothermal reservoir is overlain by the caprock composed by the Quaternary lacustrine sediments with the thickness of 0.7 to 1.6 km. It was estimated that the hot dry rocks covered an area of over 3,000 km^2 in the depth of 3 to 5 km, representing exploitable geothermal resources with the amount of 13.66 EJ. Since the geologic settings of the Gonghe Basin are comparable to that of several enhanced geothermal systems carried out in crystalline rocks, e.g. the Cooper Basin in Australia, and the Milford FORGE in the USA, the methods of reservoir permeability enhancement and long-term monitoring in these fields can be important references for future EGS demonstration in the Gonghe Basin, China.

1. INTRODUCTION

Geothermal energy is renewable and environmental-friendly, and its utilization can relax the demands of fossil fuels and solve the conflict between rapid economic development and environmental degradation. It is estimated that geothermal energy will occupy 3% of the total energy consumption in China by 2030 (Breede et al., 2013; Fang et al., 2018). However, the use of conventional hydrothermal energy at present is only available in a limited number of regions, while the majority of geothermal energy stored in the hot dry rocks (HDR) within 3 to 10 km depths is still under-exploited.

The total amount of HDR energy stored in mainland China can reach 2.5×10^7 EJ (Wang et al., 2017). To efficiently extract the thermal energy from the HDR, the permeability in the reservoir needs to be enhanced by hydraulic shear and chemical stimulation, forming an enhanced geothermal system (EGS) (Breede et al., 2013). EGS projects have been established in a number of countries including the United States, France, Germany, Japan and Australia. In China, the first EGS demonstration project will be established in the Gonghe Basin of western China this year (Xu et al., 2018a). We here review the progresses of the HDR geological exploration in the Gonghe Basin, and analyze the suitability for HDR resources exploration and development in this site.

2. STUDY AREA AND GEOLOGIC SETTING

2.1 Geologic Background

The Gonghe Basin in Qinghai Province, China, is located in the Northeast margin of the Qinghai-Tibetan Plateau. It extends in the NWW direction and covers an area of 21,186 km^2 (Fig. 1). It is a Cenozoic basin tectonically controlled by the Qinghainan Fault to the north, by the Animaqing Structure to the south, by the Wahong Fault to the west, and by the Waligong fault to the east (Yan et al., 2013). Geothermal springs outcrop along the Waligong fault zone with the temperature higher than 90°C indicate the existence of high-temperature geothermal reservoirs in the Gonghe Basin (Xue et al., 2013).

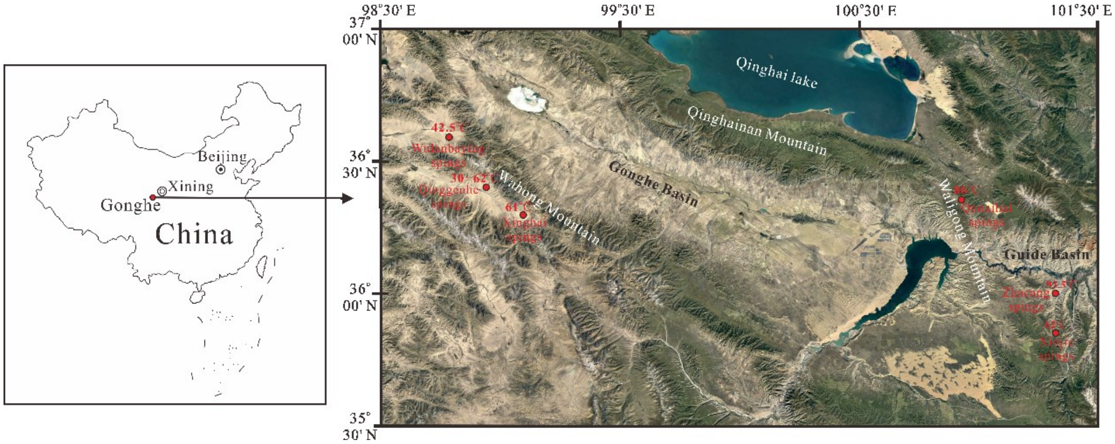

Figure 1: Location of the Gonghe Basin and geothermal spring manifests.

2.2 Geophysical Survey

The geothermal surveys in the Gonghe Basin can trace back to the 1990s and was rebooted in 2010. A 2D reflection seismic survey and potential field geophysical (aeromagnetic, magnetotelluric and gravity) explorations have been carried out to understand the geothermal system (Sun et al., 2011). The gravity and magnetic survey revealed three major geological layers: the Quaternary Formation with a thickness of about 600 m, the Paleogene-Neogene Formation with a thickness of about 800 m, and the granite basement. The high-precision aeromagnetic survey data showed the existent of high-temperature granite in the south of the Gonghe Basin at depths of 1200 to 1350 m (Zhang et al., 2018b). The seismic velocity structure showed a low velocity zone at depth between 15 and 40 km in the south part of the Gonghe Basin, indicating the existence of the melt magma chamber in middle crust (Zhao et al., 2016). Besides, low velocity anomalies were also found beneath the Eastern Kunlun and the south of Kunlun Mountain at the depth of 10 km. MT data also identified low electrical resistivity zones in the middle crust (about 15 to 35 km), which verified the existence of geothermal anomalies in the NW-SE direction, consistent with low velocity anomalies in the Kunlun Fault strike in the south of the Gonghe Basin. Inverted electrical resistivity model based on the MT data showed significantly low-resistivity anomalies at depths above 3 km, which were interpreted as widespread HDR or hydrothermal reservoirs (Gao et al., 2018). Furthermore, several hidden faults have been identified based on GPS data and surficial vertical deformation (Hao et al., 2012).

2.3 Drilling

The geothermal drilling campaign was firstly begun in 1999, to develop low-temperature geothermal water utilization in the Qiabuqia Town in the northeast of the Gonghe Basin. There are four medium-low temperature wells with depths of 969 to 1852 m exposing hydrothermal reservoirs of 70 to 98.6°C. Since 2013, four deep geothermal wells (DR4, DR3, GR1 and GR2) have been drilled to further explore the HDR resources. Those boreholes drilled into the Indosinian granite basement at depths of 2927 to 3705 m, revealed the bottom temperatures reaching 178 to 236°C. GR1 well drilled into hot dry granite attaining the highest temperature of 236°C at the depth of 3705 m, which represents the most successful HDR exploration in China (Zheng et al., 2018).

These geothermal wells are generally distributed along the Qiabuqia River valley in the NS direction. Combined with the geophysical investigation results, the regional geological structure is obtained, see Fig. 2. Downhole logs confirmed the existence of three geothermal reservoirs. The shallow hydrothermal reservoir locates at depth of 100 to 200 m with temperature of 30°C, which consists of the Lower Pleistocene fine sandstone and mudstone. The deeper hydrothermal reservoir locates at depth of 669 to 1150 m, with temperature of 65 to 96°C. This reservoir consists of the Neogene sandstone and conglomerate, where the permeability is higher than that in the shallow reservoir. Attributed to the high permeability, the free convection occurs in this deeper hydrothermal reservoir, and a lower vertical thermal gradient of 60°C/km was observed. Beneath of hydrothermal reservoirs are hot dry rocks at depths varying from 930 to 1440 m, consisting of Indosinian intermediate-acidic intrusive rocks and Triassic clastic and carbonate rocks. At depth of 1400 to 1550 m, the granite contains a large amount of weathered fractures. Due to the strong tectonic activity, drilling rock samples showed that fractured granites interbeded with the full rocks. These pre-existing natural fractures and/or joints are desirable for enhanced geothermal reservoir development. In addition, temperature logs showed a geothermal gradient of 71.4°C/km in the deep granite, which is also preferred for the future HDR development.

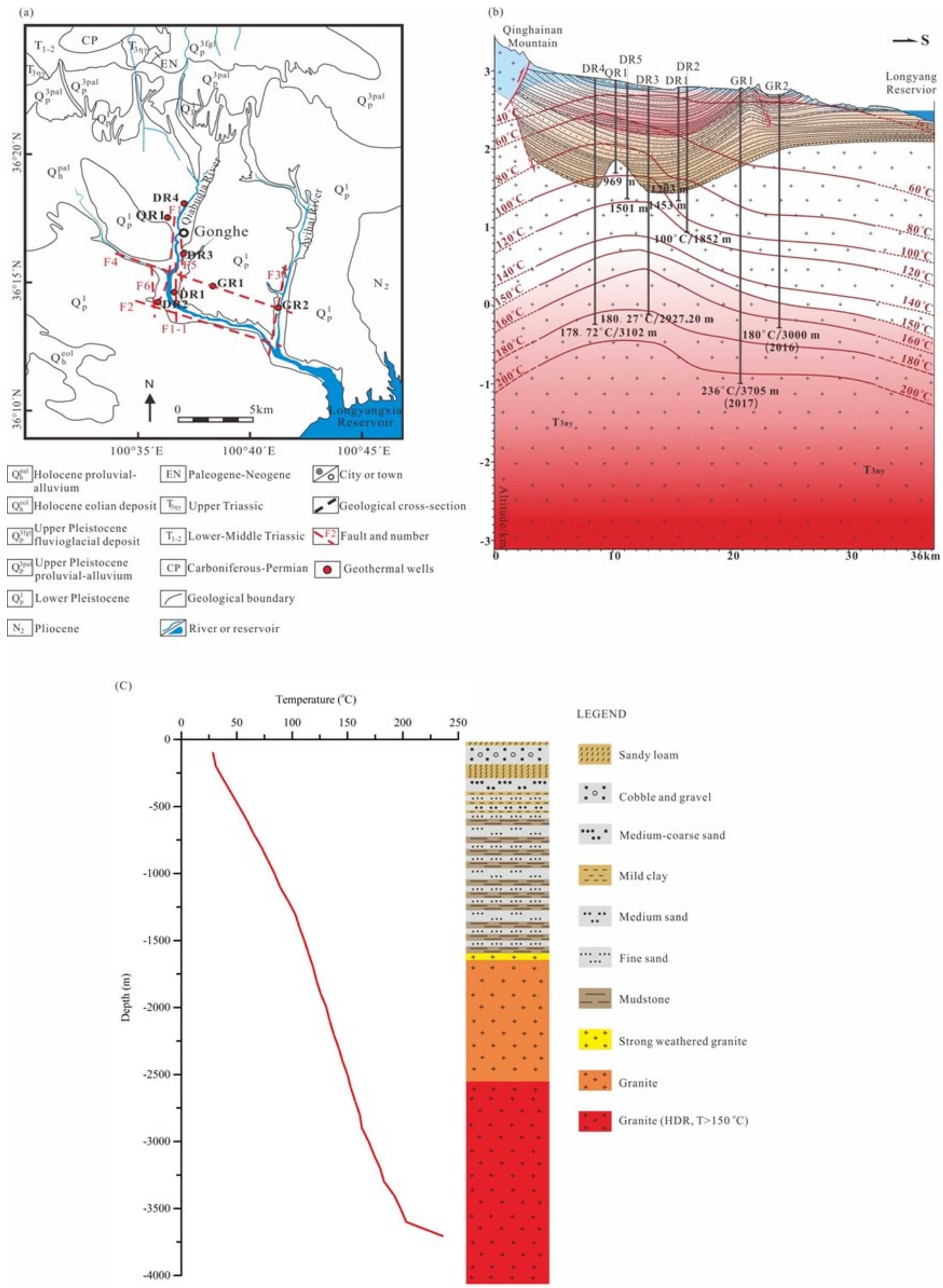

Figure 2: (a) Simplified geological map and geothermal well locations, (b) Geological profile showing two hydrothermal reservoirs and the distribution of HDR in the Qiabuqia geothermal area in the Gonghe Basin and (c) Temperature and lithology logs in Well GR1 (after Zhang et al., 2018b).

3. POTENTIAL EGS RESEARCH AND DEMONSTRATION SITE

3.1 Genesis Models of HDR

The laboratory measurements of radiogenic heat production rates in granite showed values ranging from 0.35 to 3.39 μW/m^3 (Zhang et al., 2018a). This suggested that radiogenic heat production has a limited contribution to the thermal anomaly in the Gonghe Basin. Geophysical exploration indicated the existence of partial melting of the granite in the middle crust at depths of 8 to 32 km extending in EW direction with a length of 50 km, presenting high electrical conductivity and low seismic velocity. These shallow magma chambers may originate from the crust and upper mantle caused by the uplift and denudation of the Qinghai-Tibet plateau (Li and Li, 2017), which is likely considered as the major heat source of the HDR in the Gonghe Basin.

Heat transports from magma chamber upward via the vertically elongated faults, formed in the Mesozoic-Cenozoic, at depths of 3 to 15 km. These faults connect the deep magma chamber to shallow granite rocks, and accelerate the upward heat transport. Once the heat arrived at depth of 700 to 1400 m, it was overlain by a low-permeability cap rock composed by lacustrine sediments, which can prevent heat from escaping (Fang et al., 2005).

3.2 Suitability of a Potential EGS Site

It was estimated that in the Gonghe Basin, the HDR with temperature higher than 150°C at depth deeper than 2500 m covers an area of 246.90 km^2. The total exploitable geothermal energy held by the HDR at depth of 3 to 5 km was estimated to a potential power capacity of 3805.74 MW in 100 years (Zhang et al., 2018b). We numerically evaluated the electricity generation potential in the Gonghe Basin (Xu et al., 2018b), assuming an EGS system being constructed with two horizontal wells in a fractured reservoir of 0.125 km^3 at depths between 2700 m and 3200 m. It was estimated that the designed EGS power system can attain an electric power of 3.05-3.59 MW in 30 years.

In addition to the theoretical evaluation of the HDR geothermal energy potential in the Gonghe Basin, the conditions here are compared with the US Milford FORGE site (Frontier Observatory for Research in Geothermal Energy) (Simmons et al., 2016). As shown in Table 1, the HDR site of Gonghe Basin is larger than that in the Milford site. At the depth shallower than 3000 m, the average temperature in Milford field is higher than that in the Gonghe Basin by about 20°C, while in the depth deeper than 3000 m, the temperatures in both sites become higher than 200°C. The HDRs in both sites are of crystalline rocks with initial fractures created by tectonic activities. In the Milford, high-salinity groundwater exists in the shallow geothermal reservoirs, which can be used for hydraulic stimulation in deeper hot dry rocks. While in the Gonghe Basin, plenty of surface water in Qiabuqia River and also groundwater in alluvium aquifers are available for hydraulic fracturing. The similar temperature and reservoir conditions make the experiences in the EGS project of the Milford be an important reference for the future EGS in the Gonghe Basin.

Moreover, the Gonghe Basin is located in the belt of green energy development in China, where the large solar photovoltaic power plants have been established together with a hydropower station in the Longyangxia of upstream Yellow Reservoir. The electrical power generated from the EGS can be easily transmitted via the readily available electric grid. All these conditions make the Gonghe Basin a suitable site for the first enhanced geothermal system site in China.

Table 1: Comparison of site characteristics between US Milford and the China Gonghe Basin.

Site Characteristics	US Milford FORGE	The China Gonghe Basin
Drilling Temperature	175-230°C at 2133.6～3854m, temperature gradient of 55-60°C/km	150-236°C at 2927.2～3705m, temperature gradient of 71.4°C/km
HDR Area	An area of 200 km^2, buried in 2000 m deep	An area of 246.90 km^2, buried in 2104.31-2500 m deep
HDR Lithology	Tertiary granite and Precambrian gneiss intruded by Tertiary granite	Middle-late Triassic granodiorite and monzogranite
Tectonic Location	Cenozoic basin in Basin and Range Province	Cenozoic depression basin
Tectonic Setting	Well-developed normal faults	Compressive-torsional faults and normal faults
Heat Source	Quaternary magmatic activity	Partial melting in upper crust
Ecosystem and Environmental Settings	High salinity groundwater, no endangered species, no historic and cultural sites	Abundant surface water resources

3.3 Future work

The primary geothermal exploration in the Gonghe Basin has been completed, which forms an important foundation for the first EGS demonstration site in China. In the next few years, the resolution of a regional 3D geological model will be constructed for representation of the lithospheric thermal structure and the genetic mechanism of HDR resources in the Gonghe Basin. The resolution of HDR resources potential evaluation in the basin will be further refined. The location and trajectory design of drillholes for reservoir stimulation, heat production and water reinjection will be determined. Consequently, reservoir hydraulic simulations will be conducted, together with the chemical stimulation via inclined drillhole to enhance the hydraulic connection and to develop large-scale interconnected fracture network in the EGS reservoir. The effects of the reservoir construction will be evaluated based on micro-seismic monitoring, tracer tests and trial exploitation tests. Additional drilling and reservoir stimulation will be further decided to improve the performance of the EGS system.

4. CONCLUSIONS

This work summarized the progress on the hot dry rock exploration in the Gonghe Basin, China, and demonstrated its suitability for establishing a first demonstration site of the enhanced geothermal system. The following conclusions can be drawn:

1. Drilling and geophysical survey revealed two hydrothermal reservoirs in the Gonghe Basin, underlain by hot dry rocks with the temperature exceeding 200^{o}C at the depth deeper than 3000 m.

2. The melted magma chamber at depth of 15 to 35 km forms the major heat source for the geothermal reservoirs in the depth shallower than 3000 m. Heat is mainly transferred by conduction in granite, leading to a temperature gradient of 71.4^{o}C/km in the hot dry rocks. While in the shallow hydrothermal reservoir at depth of 700 to 1200 m, convection occurs due to the high permeability in the reservoir, resulting in hydrothermal reservoirs.

3. Temperature, lithology and burial depths of hot dry rocks in the Gonghe Basin are comparable to that in the US Milford site. The experiences of enhanced reservoir engineering in the Milford can be an important reference for establishing enhanced geothermal system in the Gonghe Basin.

4. The Gonghe Basin is located in the belt of green energy development, China, where the largest solar energy plants and hydropower stations have been established. The electrical power generated by enhanced geothermal system can be an important addition for green energy development in this region.

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