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Basic Principles for Selection of HDR Target Region and Well Sites in China

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ABSTRACT

In order to exploit dry hot rocks or enhanced geothermal systems, it is critical to accurately locate an area (or zone) with a sustainable geothermal temperature (greater than 150ºC), which is buried as shallow as possible. This study presents a summary of search criteria for viable enhanced geothermal systems, based on an examination of the exploitation of the existing enhanced geothermal systems worldwide. The search criteria are: 1. The target area should be focused on the active deep fault zones as much as possible, preferably the lithospheric fault zone and the crustal fault zone. This will ensure the accessibility and control of high temperature geothermal energy from deep crust. 2.There are secondary deep fracture zones intersecting the active deep fault zones. These fracture zones serve as heat conduit channels. 3.There are hydrothermal activities or modern volcanic activities in the intersections. This indicates that the intersections are well connected to the deep crust geothermal sources. 4.The target area is covered with a certain thickness of sedimentary caprock, which is relatively enclosed to insulate and maintain the high temperature from the deep crust geothermal systems. Two types of geological structures (zones) are identified to meet all the above criteria. The first ones are located near the boundaries of grabens, which are formed as a result of lithospheric or crustal faults. The other ones are located in modern volcanic zones, which are accompanied with hydrothermal activities. Our study has shown that shallow high temperature geothermal reservoirs (3~5 km) are mostly of hydrothermal convection system. In these areas, fractures are highly developed and the geothermal gradients are steep. Generally, it is advantageous to exploit the enhanced geothermal systems in the regions that have a geothermal fluid temperature of greater than 150 ºC and a burial depth of less than 3000 m. On the other hand, the dry geothermal environment formed by the intact rock geothermal reservoirs, much deeper than the fractured zone, has low geothermal gradients. Exploitation of such hot dry rock geothermal by using hydraulic fracturing method faces not only considerably high cost but less than satisfactory outcomes.

1. INTRODUCTION

At present, the research of Hot Dry Rock (HDR) in China is in the primary stage of survey and exploration of target areas of hot and dry rocks; exploration of hot and dry rocks has been carried out in few provinces (Wang et al., 2018). Prior to this, China mainly focused on hydrothermal geothermal energy development and achieved promising results (Zhou et al., 2015). Among them, the areas of Yangbajing and Yangyi geothermal field of Tibet are 300 m deep with 180 to 200 ℃ fluids (Zhou, 2010; Wang, 2018). Zhangzhou city of Fujian province is 100 to 200 m deep with 120 to 122 ℃ fluids (Hu et al., 1999). Kangding district, western Sichuan province, has a geothermal resource located at a depth of 220 to 2500 m with 174 to 185 ℃ (Yang et al., 1999). Since 2010, the high-temperature geothermal exploration aimed at the development of HDR has explored many boreholes in the Tashkurgan valley of Xinjiang with a depth of 200 to 800 m and got temperatures ranging from 98.3 to 162.2 ℃ (Chang et al., 2016, Pang et al., 2011).

Detailed drilling was carried out in the Gonghe basin and Guide basins of the Qinghai province, and the temperatures obtained were 18 3℃, 178 ℃ and 151 ℃ at 3000 m depth, respectively (Zhang et al., 2018). In May, 2017, a high temperature of 236 ℃ was obtained by drilling at a depth of 3705 m at the edge of Gonghe basin (Wang et al., 2017). In the course of HDR exploration in the Guide basin, the discharge and injection test, pumping test, recharge test and heat transfer test have been carried out. The depth and temperature of water (wet)-heat and dry-heat reservoir, water-heat and steam resources, heat exchange capacity and power generation potential of Guide geothermal field were determined preliminary, but it provides a basis for in-depth evaluation and develop of HDR resources (Xu et al., 2015).

2. DISCUSSION AND EXAMPLES

2.1 The Characteristics of High Hot Geothermal Field

2.1.1 Yang bajing—Yangyi Geothermal Field

Yang bajing—Yangyi geothermal field are located at the southern margin of the Nyenqing Tanggula mountains with lithospheric faults on the Qinghai- Tibet plateau. It is a tensional fault-depression basin due to the action of the near north-south compressive stress. It also intersects with the secondary structural form of Nyenqing Tanggula mountain. Electromagnetic sounding (MT) measurements indicated the presence a magma mass with a low resistance and high conductor from 8 km to 10 km underground, presumably, or a cooling magma mass.

Yang bajing Geothermal Field is one of the non-volcanic high-hot geothermal fields. Temperature inside the shallow reservoir is in the range of 150 to 165 ℃ at the depth of 180 to 280 m. Temperatures around 251 ℃ are found at depths ranging from 950 m to 1350 m, while deeper than 1850 m have experienced measured temperatures as high as 329 ℃ (Duo et al., 2003).

The geothermal field of Yangyi is mainly controlled by NW and NE faults, forming a grid structure and forming a high temperate zone at its intersection. 15 boreholes have been drilled in this geothermal field, zk208 borehole is 290 m depth with 207.5 ℃. That well is north of the main fault zone. zk300 borehole is 820 m deep with 196℃ hot fluid blowing out 30 to 40 m high. The isotherms indicate that a NNW - direction fault is the main heat conduit channel for thermal fluid. The hot spring is exposed in many places of the gully and the hot fluid is flowing at about 3000 m^3/d at 60 to 80 °C. The deeper part is a Himalayan granite-porphyry ($\gamma 63\pi$). This area is a typical geothermal field formed at the intersection of a lithospheric fault zone (Nianqing Tanggula mountain range) and its associated secondary tectonic faults (Yangbajing-Angang fault zone). It has excellent conditions for developing high-temperature (enhanced) geothermal resources (Duo, 2003).

A 16MW generator has been installed in Yangyi geothermal field, which generated electricity in 2018. It has become the largest geothermal power station in China (Dai, 2018).

2.1.2 Gonghe-Guide Geothermal Field in Qinghai Province

This geothermal field is a typical convection type of fault zone at the edge of fault basin. Gonghe geothermal field is located on the southern slope of the intersection of the NW end of the Waligong mountain and the east end of the south of the Qinghainan mountains (SEE). A nasal form anticline is developed in the slope zone, and three sets of faults are distributed on it, namely NW80°, NW10° - NE20 ° tensile fault, and a near north-south fault zone. Hot springs or geothermal anomaly areas are distributed near these faults, which indicates that these faults cut deep and provide a good channel for deep thermal convection and thermal fluid migration (Sun et al., 2011).

The total thickness of 800 to 1200 m of tertiary sandstone and mudstone interbeds had been laid down in the northern Gonghe basin, and the basement is composed of Indochinese and Yanshanian granodiorite and granite ($\gamma\delta 51$、$\gamma 52$). The geothermal gradient of the rock mass is 57.1 to 71 °C/km. The rock mass of 3000 m deep has a temperature above 180 °C, and the highest observed temperature is 237 °C in 3270 m deep rock (Zhang et al., 2018).

Guide geothermal field is mainly composed of NNW, NE and EW fault zones. According to MT and other measurements, the NW trending fault zone (Qilian mountain, laji mountain, qinghai lake nanshan, etc.) is a lithospheric fault zone with a cutting depth of 80 to100 km. In the fault zone, many hot springs have 80 to 96 °C temperatures. The sedimentary cover is the tertiary mudstone and sandstone interbedded, and the partial sections are Triassic slate and quartz sandstone, with a total thickness of 500 to 1500 m. The basement is granitoids (γ 51 γ 52) of the Indo-Chinese and Yanshanian period (Li et al., 2016). Guide Zacanggou geothermal field has observed temperatures of 151 °C at 3050 m, and 214 °C at 4602 m.

2.1.3 Kangding Geothermal Field of Sichuan Province

Kangding geothermal field is one of the main seismically active zones in NNW Xianshuihe active fault zone. Several geothermal anomalies are distributed along the fault zone. In the area from Kangding county to old Yulin town, the geothermal field is controlled by the intersection of NNW and NEE faults. There are more than 20 hot springs in the valley, and their temperatures are greater than 60 °C. At the junction of the faults, the temperature is higher and steam is ejected.

On both sides of the valley are older metamorphic rocks, and the valley is a quaternary deposit with a thickness of 50 m. In this section, the geothermal well depths are: 221 m with a borehole bottom temperature of 174 °C, and 230 m with 182°C. It is estimated that at 1000 m depth, temperatures will be greater than 250 °C (Sun et al., 2019).

2.1.4 Tengchong Geothermal Field of Yunnan Province

Tengchong geothermal field is located in the suture zone where the Eurasian plate meets the Indian plate. Hot springs and volcanoes have been distributed in many places since the Cenozoic era. A low resistance band of depth of 2 to 5 km was measured by MT and a magma chamber was speculated to exist deeper than 7 km depth. The temperature is above 300°C. The deposition cover is thinner. The hot spring on the surface is greater than 90 °C, and is boiling (Liao et al., 1997; Bai et al. 1997).

At present, there is no 3 to 5 km deep drilling to expose the geothermal field. The deep geothermal reservoir needs to be explored more with detailed geological exploration. This area is an ideal target area for developing HDR geothermal energy.

2.1.5 Baoting and Danzhou Geothermal Field in Hainan Province

Hainan island is surrounded by lithospheric cracking and stretching from the early Yanshan period. An east - west (E-W) structure is formed, which is Qiongbei fault basin. Since the Cenozoic era, Cenozoic sedimentary rocks and volcanic eruptive rocks（Quaternary basalt） have been distributed at the edge of the basin, that is an indicated lithospheric fault. A large area of Indosinian granite is exposed in the south of the fault zone, and the NE, NWW and NW trending secondary structures across with them. Where the faults meet site, there are hot spring outcrops, including Danzhou blue ocean hot spring at 80°C and Baoting Qixianling hot spring at 90°C. Sedimentary cover is thin, and it is mainly igneous regolith (Gao et al., 2003; Chen et al., 2008).

A well with a depth of 4387m was completed in Chengmai county, with a bottom-hole temperature exceeding 185 °C for HDR and a geothermal gradient of 37 °C/km. Within the range of 590 km^2 of Fushan fault basin, a HDR area of 98km^2 can be developed to the depth of 4500 m with greater than 180°C temperatures. There are abundant HDR resources in the Fushan fault basin and Qiongbei area.

2.2 Potential Geothermal Field

Tianzhen Majuanxiang—Yanggao Gushanmiao geothermal field is a potential target area via the analysis in Datong city, Shanxi province.

2.2.1 Geotectonics

The geothermal anomaly areas of Tianzhen Majuanxiang – Yanggao gushan temple are located in the first-level tectonic fault block of Inner Mongolia, and the anomaly areas are located in the spiral tectonic area of Yanggao-Tianzhen.

The second-order thermal control fault is a NNW-trending fault zone and NEE zonal tectonic fault zone. NNW five multistep faults control heat. Two Paleozoic metamorphic thermal reservoir horst uplift areas were formed in Shuitong temple and Majuanxiang, and many Yanshanian granite and diabase dikes intruded into the basement, overlying the Cenozoic loose cover layer of 290 m. The horst and deep faults are the deep heat source channels (Wang et al., 2014).

2.2.2 Geophysics

Magnetotelluric sounding, according to the resistance rate of 2 to 5 Ωm in the middle crust, have a low speed, high conductivity layer. The thickness is 4 km, located at about 14 km depth in the basin. Analysis of the layer points to a cause by a material of high temperature molten rock (Bai et al., 1994).

2.2.3 Comprehensive Analysis

The depth of geothermal well D1 in Tianzhen Shuitongsi is 500 m, the lithology of the borehole bottom is gneiss, the water temperature of the well head is 104.3℃, and the temperature of the borehole bottom is 116.25℃. The average geothermal gradient is 10.2 ℃/100m, and some sections are 14 ℃/100m. The depth of D4 in Pingshan village, Yanggao county is 178 m. The rock at the bottom of the borehole is a pebble layer of lower Pleistocene (Q1). The wellhead water temperature is 104℃. It is expected to be greater than 180 ℃ at 2000 m depth. The geothermal fields of Majuanxiang in Tianzhen and Gushanmiao in Yanggao were selected as the target areas for HDR development (Yang et al., 2014).

2.3 Characteristics of Pre-selected Target Area

(1) The geothermal anomaly area is located in lithospheric or crustal fault zones, as well as near basement fault zones that serve as deep heat sources in geothermal fields.

(2) The secondary fault zone (tectonic zone) intersects with the large fault zone, and that is as deep as possible. This fault zone provides a transmission channel for thermal energy.

(3) Hydrothermal activity with geothermal field or hydrothermal display since Cenozoic era. That indicates the smoothness of heat conduction channel.

(4) The sedimentary cover plays a role in heat preservation of underground heat reservoir.

The geothermal geological conditions of these examples are in line with the basic conditions for the development and utilization of HDR in the world (Brown et al., 2012; Baticci et al., 2010).

2.4 Target Area Exploration Contents

Additional work is necessary for the selection of target areas.

(1) analysis of geological data: Firstly, the location and nature of major abyssal fault zones (lithospheric faults, crustal faults or basement faults), as well as secondary structures associated with their genesis, are determined in the areas to be worked on using existing data. The possible sources of geothermal sources, namely the controlled construction of the main thermal channels, are analyzed.

(2) Geological survey (more than 1:10,000 in mountainous areas); including key geological structures, volcanic distribution, formation lithology, hot spring, borehole temperature measurement and water quality measurement. Monitoring of surface water (river water), hot spring flow and water quality in a hydrological year. The distribution characteristics and present situation of thermal anomalies are determined.

(3) Temperature measurement; in a grid (or 2m deep) of surface, with points 5 to 10 m or 50 to 100 m apart (depending on the working range or the range of hot springs and wells with thermal anomalies), and to understand the distribution characteristics of concealed thermal anomalies in the working area.

(4) Radon gas measurement; the underground 30 to 50 cm should be arranged in the same place as the temperature measurement. Determining the reflected location of buried fault zone on the surface.

(5) Remote sensing interpretation: use multi-band and large-scale satellite images to identify surface geological structures. Thermal anomaly distribution rule is explained by large scale (1:10,000 or larger) thermal (far) infrared film. The structure of the research area and its thermal display are analyzed in combination with Google earth or Bing map.

(6) Magnetotelluric measuring (MT)；Grasping the extended depth and tendency of the fault zone, and determining whether the nature of the fault zone (lithosphere or crust fracture) affects the upper mantle (asthenosphere), that is, reaching the hot heat source area.

(7) Gravity measurement (scale > 1:10,000 to 1:50,000); to identify the authenticity of apparent resistivity changes in the profiles of controlled Source Audio Frequency Magnetotellurics. Grasp the trend, strike and inclination of fault zones, as well as the distribution and relationship of secondary fault zones.

(8) Magnetic measurement (scale > 1:1-1:50,000); to combine with gravity measurement results and other information to determine the nature of the fault zone.

(9) Large scale (> 1:10,000) measuring is carried out in the target area by the controlled Source Audio Frequency Magnetotellurics (CSAMT) and the depth of measure can be controlled at 3,000 to 5,000 m. The specific location and occurrence (dips and dips of angle) of all fault zones were determined in the region.

(10) Artificial seismic measurement to determine the nature (normal and reverse faults, influence depth) and occurrence of fault zones in the sedimentary layer (overburden). Know whether the basement fault extends to the cover or whether the two are connected in other directions. The thermal anomaly sources and distribution characteristics of the cap layer are analyzed.

3. CONCLUSION

In recent years, other provinces in China have also carried out the exploration of hot and dry rocks to varying degrees. However, due to the lack of detailed investigation, measurement and analysis in the preliminary work, the drilling temperature is relatively low. Therefore, accurate determination of drilling location is very important. This paper summarizes the main methods and contents of HDR exploration to improve the success rate of drilling.

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