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Target Selection of Enhanced Geothermal System in Shandong Province

JIANG Haiyang[1,2]，WANG Shuxing[2]，KANG Fengxin[3,4]，ZHANG Ling[5]，SHI Meng[6]

1.College of New Energy and Environment，Jilin University，Changchun，Jilin 130061，China

2. The First Institute of Geology and Mineral Exploration of Shandong Province，Jinan，Shandong 250014，China

3. Shandong Provincial Bureau of Geology & Mineral Resources, 250013 Jinan, China

4. Shandong Provincial Research Center of Geological Survey Engineering Technology, Jinan，Shandong 250014，China

5. Shandong New Energy Limited Company of Geology and Mienral Resources，Jinan，Shandong 250014，China

6. The 3rd Institute of Geology and Mineral Exploration of Shandong Province，Yantai，Shandong 264000，China

kangfengxin@126.com[3,4]

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ABSTRACT

Hot dry rock is an abnormal high-temperature rock mass which does not exist or only has a small amount of fluid. Its energy is huge, and its development and utilization process is clean and pollution-free. It is a potential energy source in the future. High-efficiency exploration and development technology of HDR were actively explored all over the world.. Shandong Province is one of the earliest provinces to exploit and utilize geothermal resources in China. It has also made active exploration in the searching of HDR geothermal resources. This paper reviews the exploration and practice of HDR exploration in Shandong Province. Combined with several typical HDR exploration projects, such as in Dongying Lijin and Weihai Wendeng, the technical methods of target selection and resource evaluation of HDR were summarized. The background conditions for the formation of HDR are analyzed and the genetic types of HDR were classified. The geological models of dry-hot rocks of different genetic types were summarized and established, and the favorable target areas for the occurrence of dry-hot rocks were predicted.

1. EXPLORATION HISTORY AND EXPLORATION MEANS OF DRY HOT ROCK RESOURCES IN SHANDONG PROVINCE

A 2500m deep dry hot rock exploration hole (GRY1) was constructed in the Chenzhuang uplift area of Lijin County, Shandong Province in 2011. The fracturing test of granite was carried out at the bottom of the hole at 109 degC (Tan xianfeng et al., 2015, 2016). In 2013, the project of investigation and evaluation of dry-hot rock resources potential in Shandong Peninsula Blue Economic Zone was implemented. The bottom temperature of thermometric borehole ZKCW01 is 114.12 degC(Jiang Haiyang et al., Tian Liqiang et al., 2016).

In addition, several scientific research projects have been carried out, such as the study of dry-hot rock geothermal resource selection in Shandong Province, the study of dry-hot rock selection in Shandong Province, and the investigation of deep geothermal accumulation areas in eastern Shandong Province. These projects are financially funded with limited funds, mainly in the pre-feasibility stage of exploration. The means of work are geothermal geological survey, geophysical prospecting, geothermal field measurement, rock and mineral testing. Generally, it does not involve drilling or only temperature measurement hole drilling and temperature measurement. The drilling depth does not exceed 2500m, and the temperature has not exceeded 120 degC. The overall technical level is not high. It still stays in the stage of exploration selection, geophysical exploration methods, drilling technology exploration and numerical simulation, and has not yet involved in engineering application. Three thermometric boreholes have been constructed, one in sedimentary basin area, one in tectonic active area and one in modern volcanic area. Some progress has been made in Lijin and Wendeng projects. The results of Jinan gabbro drilling are similar to those of Wudalianchi dry-hot rock drilling in Heilongjiang Province, which proves that the distribution area of basic volcanic rocks is not conducive to heat accumulation of dry-hot rock. (Zhang Ling et al., 2018; Cao Yanling et al., 2018; Du Xianjun et al., 2017).

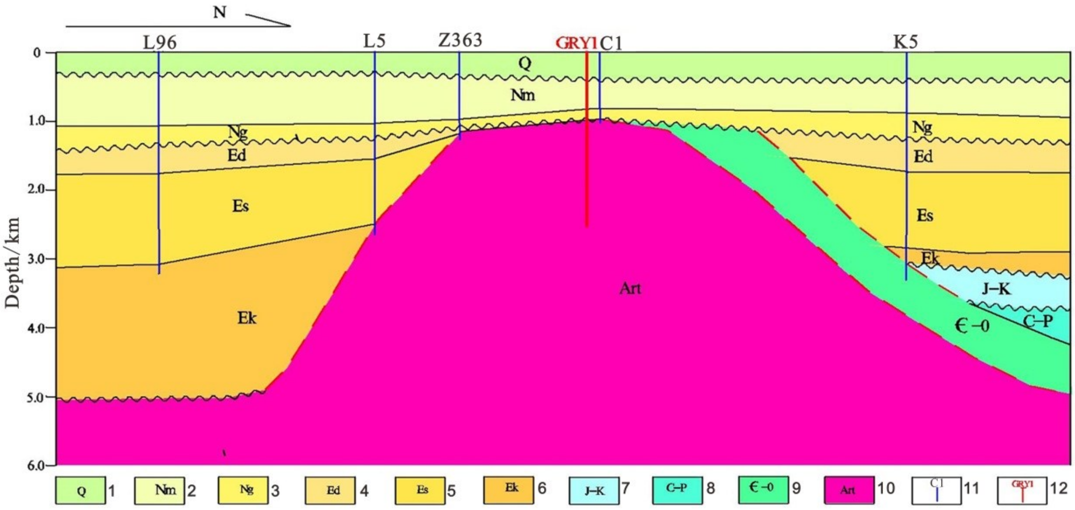
2. GENETIC TYPES OF DRY-HEAT ROCKS IN SHANDONG PROVINCE

According to the background of China's crustal structure, the occurrence types of dry-hot rock resources in China can be divided into high radioactivity heat-producing type, sedimentary basin type, modern volcanic (magmatic) type and strong tectonic active belt type. (Gan Haonan et al., 2015).Based on the analysis of geological characteristics of Shandong Province, the main types of dry-hot rock occurrence in Shandong Province are sedimentary basins type represented by Northwest Shandong Province and modern intrusive rocks superimposed by strong tectonic activities type represented by Eastern Shandong Province.

2.1 Sedimentary basin type xerothermal rocks

Sedimentary basin-type dry-hot rock resources are characterized by large thermal insulation cover thickness, high geothermal gradient and stable temperature increase. When the deep heat source conducts upward to the overburden, the heat loss is reduced due to the low thermal conductivity of the sedimentary overburden. Although the surface heat flow value of this kind of dry-hot rock resources is not very high, because of the accumulation of heat in the shallow part, the temperature of the base rock mass at the bottom can reach more than 150 C. The main representatives are Jiaolai Basin and the buried convex area of Northwest Shandong Plain. Northwest Shandong buried uplift area lies to the north of Qiguang fault and west of Liaokao fault. It is a Mesozoic and Cenozoic fault basin. The basin subsided in Cenozoic, accepting Paleogene and Neogene deposits. The ancient basement is Archean metamorphic rock. The thermal storage floor of Guantao Formation is 1000-2300m deep and the water temperature is 45-

65 degC；The thermal storage floor of the Paleogene Dongying Formation is 1 200-2 000 m deep and the water temperature is 50-74 degC；Paleogene Shahejie Formation thermal storage, the floor depth is generally 1200-2500m (the deepest 2900-3500m), water temperature is 65-90 degC；Ordovician-Cambrian carbonate rock fractured karst thermal reservoir, roof depth 1000-1700m (the deepest 3200m), wellhead water temperature 60-100 degC(Wu Lijin et al., 2016; Tan Zhirong et al., 2018)。Pre-Paleogene strata are absent in Ningjin, Wudi, Chenzhuang and Qingtuo uplifts. Neogene Guantao Formation thermal reservoirs are mainly developed, with a floor depth of 1400-1500m and a water temperature of 45-65 degC，The geothermal gradient is 3-6 degC/100m ，According to the selection index of target area of dry-hot rock such as temperature field, low thermal conductivity caprock and high temperature rock mass, it is a good area for the occurrence of dry-hot rock. This inference has been confirmed by the exploration hole of dry-hot rock in Chenzhuang uplift of Lijin County.

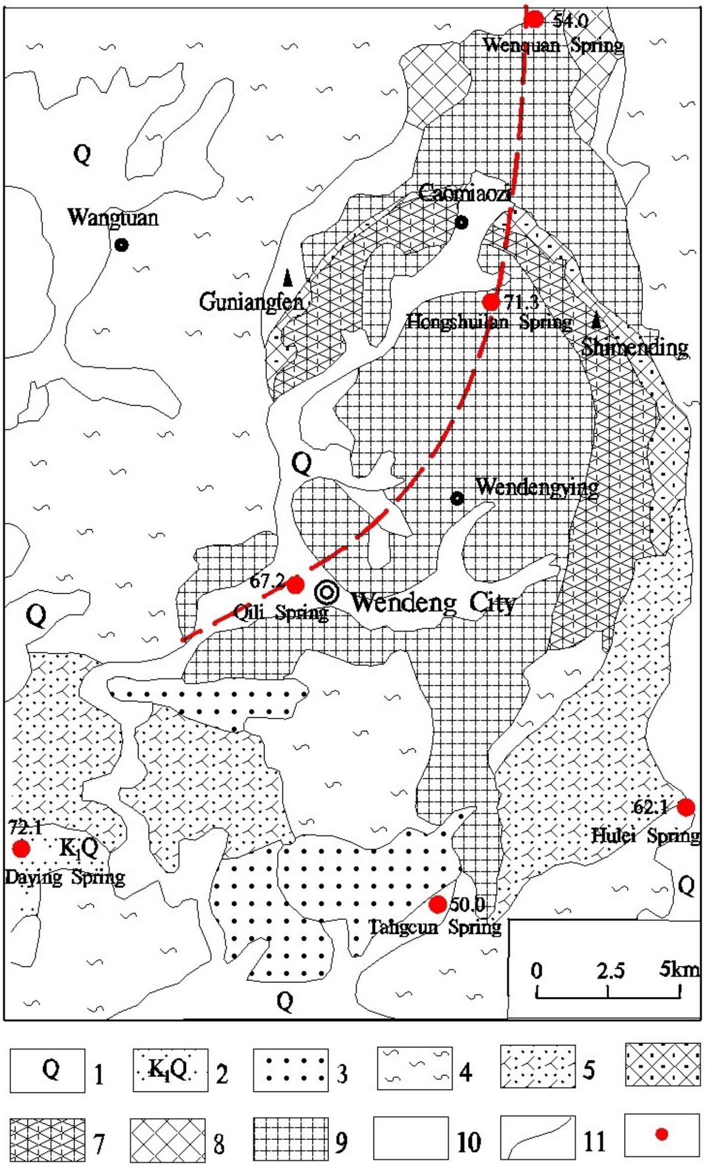


1-Quaternary Plain Formation; 2-Neogene Minghuazhen Formation; 3-Neogene Guantao Formation; 4-Paleogene Dongying Formation; 5-Paleogene Shahejie Formation; 6-Paleogene Kongdian Formation; 7-Jurassic-Cretaceous; 8-Permo-carboniferous; 9-Cambrian-Ordovician; 10-Archean Taishan Group; 11-Petroleum holes; 12-Dry-hot Rock Exploration Hole

Figure 1: Model Diagram of Sedimentary Basin Type Dry-hot Rocks（According to Wang Hao et al.，2014）

2.2 Strong tectonic activity superimposed modern intrusive xerothermal rocks

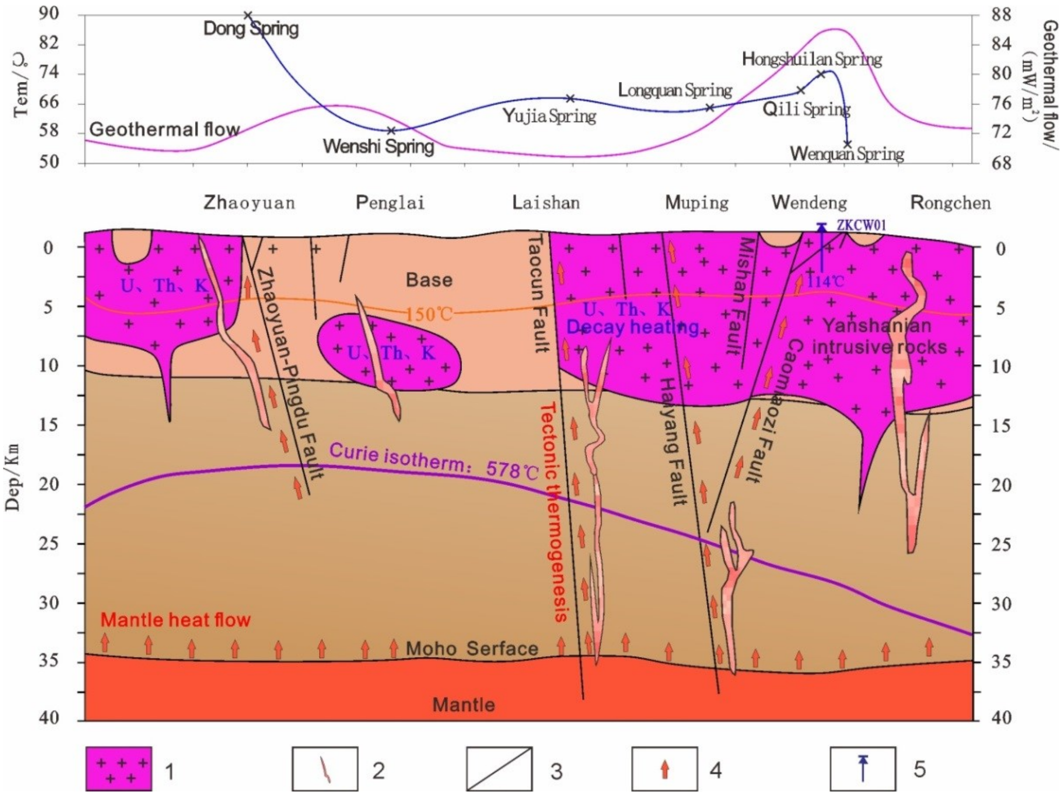
Strong tectonic activities superimpose modern magmatic xerothermal rocks, mainly representing the Jiaobei massif. Jiaodong Peninsula is situated in the subduction zone of the Pacific plate margin. It is subducted and compressed by the Pacific plate, and formed a high geothermal gradient zone by the Himalayan intrusive and extrusive rocks developed along the Tanlu fault zone. At present, the Wulian-Qingdao fault and Jimo-Muping fault are commonly called the Wulian-Yantai fault as the demarcation line between the Jiaobei massif and the Sulu orogenic belt. Aeromagnetic data interpretation shows that there are magnetic bodies in the North China plate beneath the Sulu high-pressure-ultrahigh-pressure metamorphic rocks. It shows that there is also intense compression subduction and heat generation between the North China plate and the Sulu UHP metamorphic rock belt. The subduction, superimposition and compression of the three plates (Pacific plate, North China plate (Jiaobei block) and Sulu high-pressure-ultrahigh-pressure metamorphic rock belt from bottom to top are beneficial to the occurrence of shallow dry-hot rock geothermal resources. In addition, in the area where hot springs are exposed and concentrated in Jiaodong, geothermal temperature is distributed around a central rock mass. The temperature near the rock mass is high and the temperature far from the rock mass is low. The surface geothermal display area is small and dotted. There are many natural hot springs near Wendeng rock mass, such as Hongshuilan spring, Wenquan spring and Qili spring. The temperature of Hongshuilan spring in the central area of the rock mass is 71.3 degC, and that of Tangcun spring in the margin of the rock mass is 50 degC(Figure 2). The Mesozoic magmatic activity in Jiaobei area is intense. Magma heats the surrounding rocks, which makes the lower crust, the middle crust and the upper crust relatively short. Keep high temperature for a period of time (Figure 3).



1- Quaternary；2- Cretaceous Qingshan Group；3- Late Triassic Chaoshan Superunit Yuankuang Unit；4- Nanhua system；5- Early Cretaceous Weideshan superunit Buluojiang Unit；6- Mid-Jurassic Wendeng Superunit Caomiaozi Unit；7- Middle Jurassic Wendeng Superunit Shimending Unit;8- Middle Jurassic Wendeng Superunit Xiaoqikuang Unit 9- Middle Jurassic Wendeng Superunit Yekou Unit；10- Mid-Jurassic Wendeng Super Unit Guningfen Unit；11- Geological boundary；12- Hot Springs and Temperature

Figure 2: Wendeng Rock Mass and Distribution Diagram of Hot Springs

In 2015, the first geological and Mineral Exploration Institute of Shandong Province drilled ZKCW01, a thermometric borehole with a depth of 2000.76m, near the thermal conductivity structure of Wendeng rock mass. After 80 hours of well temperature stabilization, the quasi-steady temperature measurement was carried out, and the hole bottom temperature was 114 degC. The non-linear fluctuation of the shallow temperature measurement curve was obvious at 1900m, and the geothermal gradient changed greatly. There are four abnormal high value zones of geothermal gradient in ZKCW01, with an average geothermal gradient of 5.3-18.59 degC/100m, showing convective characteristics. The geothermal gradient of 1900m increases linearly with deep temperature, and is nearly stable. The average geothermal gradient is 1.85 degC/100m, which has conductive characteristics (Figure 4). Using the geothermal gradient of the stable conduction section, the deep temperatures of 3000m, 400m and 5000m are predicted to be about 133 degC, 150 degC and 170 degC.



1- Intrusive rock mass；2- Dike；3-Fault；4- Heat flow；5- Dry-hot Rock Exploration Hole

Figure 3: Strong Tectonic Activities Superimposed Models of Modern Intrusive Dry-hot Rocks

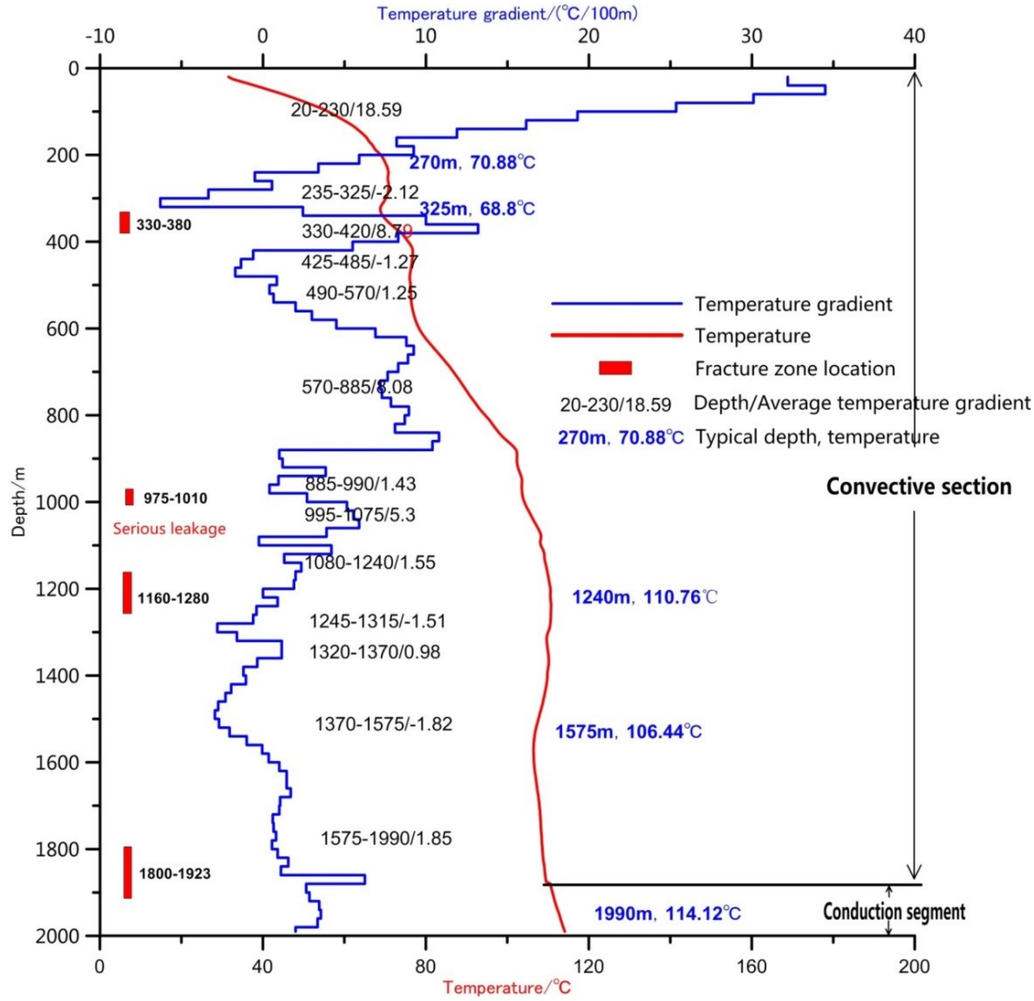


Figure 4: Temperature Measurement Curve of ZKCW01

3. POTENTIAL ANALYSIS OF DRY-HOT ROCKS IN SHANDONG PROVINCE

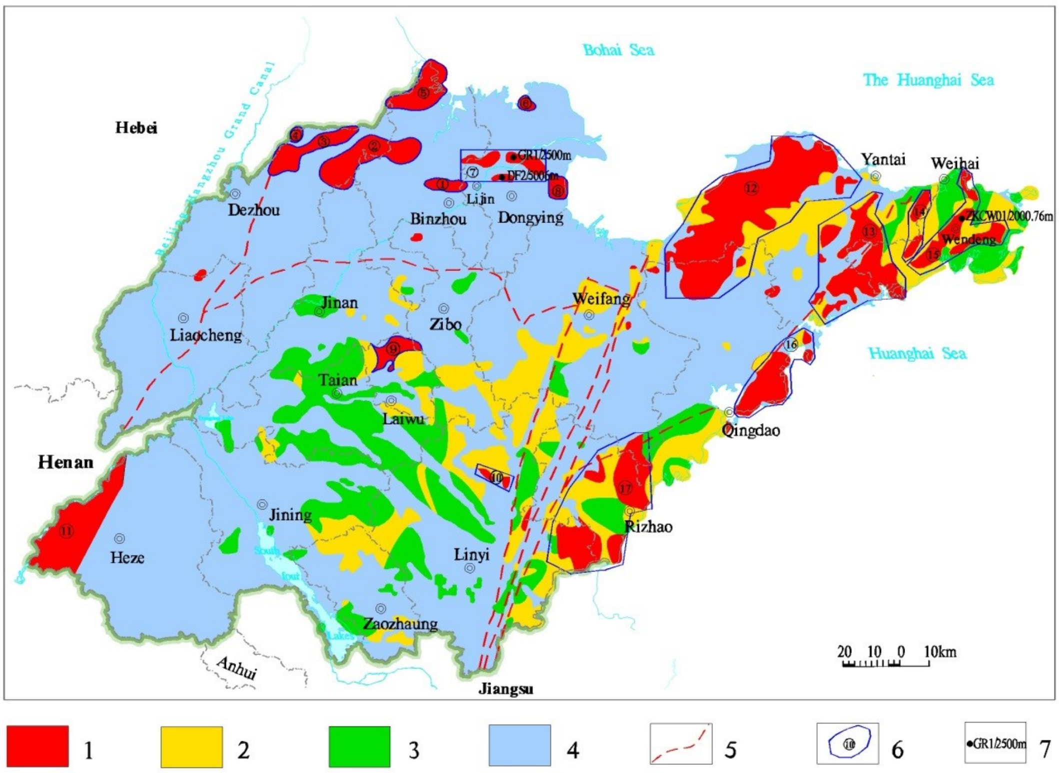
3.1 Dry-hot Rock Target Area in Shandong Province

Referring to the evaluation criteria for targets of dry-hot rocks proposed by the Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences (Ma Feng et al., 2015), six outstanding geothermal characteristics indicators, including geothermal flow value, lithology of thermal reservoirs, crustal stability, burial depth, radiogenic heat generation rate and geothermal gradient, are selected to screen Dry-hot Rock Targets in Shandong Province by comprehensive information overlapping method

Taking the distribution map of intrusive rocks in Shandong Province as the base map, the intrusive rocks are divided into 7718 small units with an area of 2 km *2 km per unit. The six indicators are divided into four grades: A, B, C and D, corresponding to 4, 3, 2 and 1 points respectively, and given different weights according to expert opinions (Table 1).

Table 1: Evaluation Criteria of Geothermal Geological Indicators in Dry Hot Rock Target Area of Shandong Province

Indicator Value	Criteria for evaluating indicators					
	Geothermal flow/ (mW/m^2)	Lithology of thermal reservoir	Crustal stability	Depth of this isothermal surface /km	Radioactive heat generation rate / ($\mu W/m^2$)	Geothermal gradient / (degC/km)
A	≥75	Granite,granodiorite	Stable	≤20	>4	>40
B	65-75	Gneissic granite	Less-stable	20-23	3-4	35-40
C	55-65	Tuff	Instable	23-26	2-3	30-35
D	45-55	Others	-	>26	<2	<30
Weight	1	0.6	0.6	0.8	1	1



1- Key exploration areas；2- Subkey Exploration Areas；3- General exploration area；4- Prospective exploration area；5-Fault；6- Key Target Areas and Numbers of Dry-hot Rocks；7- Existing exploration holes and depth

Figure 5: Classification Map of Dry-hot Rock Geothermal Resources in Shandong Province

By synthesizing and overlapping the results, the total zones are 6.2-18.2, which can be divided into four grades, with scores of 12-18.4 as key exploration areas, 10.4-11.8 as sub-key exploration areas, and 6.2-10.2 as general exploration areas. Among them, the key dry-hot rock exploration area covers an area of 15 531.24 km^2, the sub-key dry-hot rock exploration area covers an area of 20 913.25 km^2, the general dry-hot rock exploration area covers an area of 13805.5 km^2, and the rest are prospective dry-hot rock exploration areas (Figure 5).

3.2 Assessment of Dry-hot Rock Resources

The amount of geothermal resources contained in dry-hot rocks depends on the temperature of dry-hot rocks and the thermophysical properties of dry-hot rocks. Volume method is used to estimate dry and hot rock reserves in Shandong area.

$$Q=\rho \cdot C_p \cdot V \cdot (T-T_o)$$

In the above formula，Q is the reserves of dry and hot rock resources; P is the density of rock; P is the specific heat capacity of rock; V is the volume of rock; T is the rock temperature at a specific depth; To is the average surface temperature or a specific reference temperature(Wang Jiyang et al., 2012; Lin Wenjing et al.,2012; Wang Guiling et al., 2018).

The total dry-hot rock resources of 3-6 km in Shandong Province are 8.177×10^{22}J， equivalent to 2.791×10^{12}t of standard coal; 2.671×10^{23}J of 3-10 km dry-hot rock resources and 9.116×10^{12}t of standard coal. According to 2% of exploitable resources, the available amount of 3-6 km dry-hot rock resources in Shandong Province is 1.635×10^{21}J, equivalent to 5.581×10^{10}t of standard coal; the available amount of 3-10 km dry-hot rock resources is 5.342×10^{21}J, equivalent to 1.823×1011t of standard coal, which is 470 times of the total annual energy consumption of Shandong Province (total energy consumption of the province in 2015 is 387 million tons of standard coal).

3.3 Numerical simulation of dry hot rock power generation

Dry-hot rock is mainly used for power generation. Taking the measured data of Wendeng dry-hot rock temperature measurement hole as parameters, the feasibility of dry-hot rock power generation under the mining mode of "three vertical wells" (middle injection and two side pumping) is simulated by TOUGH2 software. The connection of the three wells is parallel to the direction of the local maximum horizontal principal stress. The part of 3900 m-4000 m is the drainage part. The injection rate of the target reservoir is reformed by fracturing with low injection velocity for a long time, combined with chemical fracturing and hydraulic fracturing with large displacement, until the flow impedance of the target reservoir is less than 0.1 MPa/(kg/s). It is assumed that the length, width and height of the reformed reservoir are 1000 m, 500 m and 100 m respectively. Fractured reservoirs are treated as equivalent porous media.

The simulated rock sizes are 1200 m*1000 m*300 m, and the meshes in x, y and z directions are 48, 22 and 10, respectively. The mesh is densified near the well and the fracture layer is densified. Grid 0-300 corresponds to real strata 3900m-4000m. The temperature of thermal reservoir is set to 168 degC. Density, porosity, thermal conductivity and specific heat capacity are derived from the thermal physical properties of granite cores. Shallow groundwater is used as injection water, the temperature is set at 17 degC, and the injection velocity is set at 30 kg/s. The duration of continuous operation of the whole project is set at 20 years (Table 2).

Table 2： Numerical simulation parameters

Parameter	Value	Parameter	Value	Parameter	Value
Density	2450 kg/m^3	Specific heat Capacity	1100 J/（kg·K）	Porosity	1%
Permeability ($k_x=k_y=k_z$)	$1\times10^{-17}m^2$	Borehole Pressure	P=40-10000Z（MPa）	Productivity index	$5\times10^{-12}m^3$
Thermal Conductivity	3.0 W/（m·K）	Injection Velocity	30 kg/s	Flow pressure in Pumping wells	40MPa

The output water temperature can be divided into stable stage (0-5 years) and decreasing stage (5-20 years). In the 20th year, the temperature dropped to 149 degC, which was 11.3%. Pore pressure at injection point increased from 40 MPa to 42.27 MPa in 20 years, up to less than 3 MPa, within the allowable range. It can ensure smooth circulation of water flow in 20 years. According to the 20% thermal conversion efficiency, the calculated power generation varies from 3.7MW to 3.4MW in 20 years, slightly higher than that of Soultz in France.

The following chart shows the evolution of reservoir temperature field in the past 20 years (y = 500m plane). With the injection of cold water, the temperature cold front moves gradually from the injection well to the pumping well. Because the permeability of the fractured reservoir is much higher than that of the surrounding rock, the temperature drop is also higher than that of the surrounding rock (Figure 6).

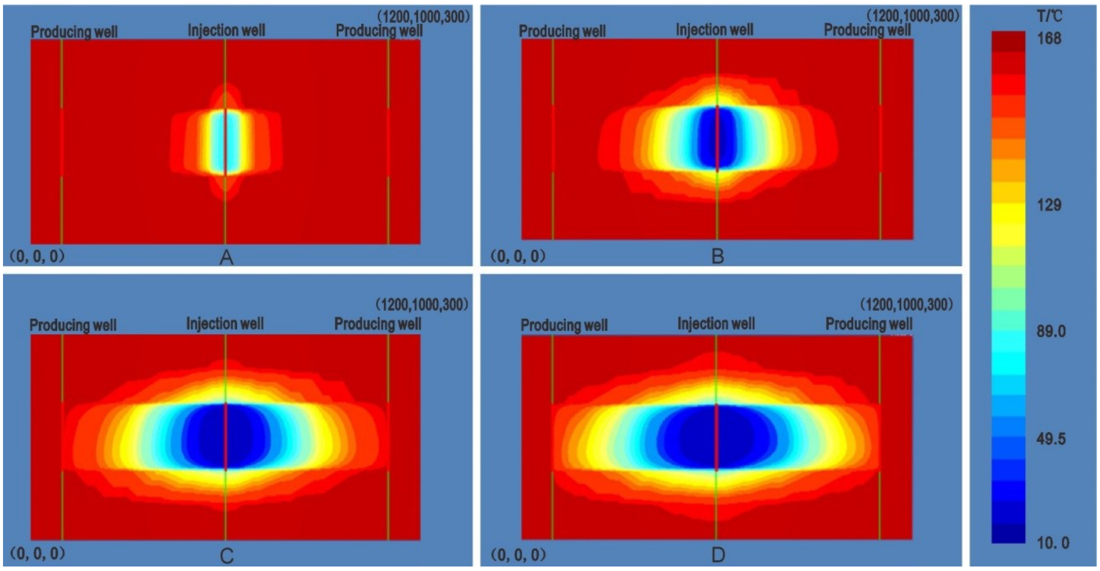


Figure 6: Evolution of Reservoir Temperature Field in 20 Years

4. CONCLUSION AND PROSPECT

1. The dry hot rock exploration in Shandong Province started early, and has carried out the pre-feasibility exploration in some areas and the study of dry hot rock target areas in the whole province. At present, the exploration funds are low, and it is still in the preliminary stage of exploration selection and related technology research.

2. The two main Existence Types of Dry-hot Rocks with Exploration Value in the Province are sedimentary basins type represented by Northwest Shandong and modern intrusive rocks superimposed by strong tectonic activities type represented by Eastern Shandong.

3. The tough 2 numerical simulation shows that the production plan of one injection well and two production wells after artificial stimulation of thermal reservoir in dry hot rock of the study area. With the injection rate of 30kg/s and the injection water temperature of 1761C, the power generation changed from 3.7MW to 3.4MW in 20 years, slightly higher than that in Soultz, France.

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