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Research Progress and Revelation of HDR Geothermal Resources in Shandong Province

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ABSTRACT

The hot dry rock (HDR) resource is abundant, widespread, and has excellent developing potential as a geothermal geological resource. China has plenty of HDR geothermal resources, which can be considered a new clean, renewable energy with considerable potential for productivity. Shandong province always has high energy resource consumption, and its demand for energy sources keeps increasing. Although the development of middle and deep HDR geological geothermal resources can enhance the energy resource supply ability of Shandong Province., the prospecting, development, and utilization of the HDR resources in Shandong province are mostly limited to shallow hydrothermal geothermal resources. Therefore, in response to the development goals of "Peak Carbon Dioxide Emissions" and "Carbon Neutrality", the research on HDR geothermal resources in Shandong is developing rapidly. Through literature collection, it can be known that Shandong Provincial Lubei Geo-engineering Exploration Institute has discovered a superior prospect area for HDR geothermal resources exploration and development in Chenzhuang latent uplift area of Lijin County, which the radioactive element generates the heat source. The Shandong Peninsula is located near the junction zone of the plate tectonics with intrusive granite widely distributed, and there is a prospect area of middle and deep HDR resources of the tectonic active belt type in the Wendeng district. Based on the HDR resource exploration and research achievements in the Wendeng and Lijin districts, Shandong Province, this paper summarizes, discusses, and analyzes HDR exploration and development research progress in Shandong Province. Combined with the occurrence conditions and heat generation mechanism of the HDR resources in Wendeng and Lijin districts and the occurrence conditions and the heat generation conditions of deep geothermal resources in Shandong province and its offshore areas, this paper discusses and conjectures the heat occurrence mechanism and distribution of the HDR geothermal resources in Shandong province and its offshore areas. Otherwise, the developing orientation and the problems and difficulties encountered in exploring and developing the HDR resources in Shandong Province are analyzed and speculated.

1. INTRODUCTION

The HDR geothermal resources align with the development goals of "carbon peak" and "carbon neutral" as they are clean, efficient, multi-component, low-carbon, and sustainable. Developing HDR's geothermal resources is a crucial step in this direction. Considering reserves, China's geothermal resources are plentiful, and the quantity of high-density reservoirs (HDR; 3–10 km) is equivalent to 860 trillion tons of standard coal, which is extremely abundant (Xu et al., 2021). Shandong Province has a large energy resource consumption, and its demand for energy keeps growing. However, HDR resources' exploration, development, and utilization are still in the initial stage. The exploitation of HDR geological geothermal resources can enhance the energy supply guarantee ability of Shandong Province (Yin and Dong, 2007; Wang et al., 2012; Lin et al., 2013). According to the economic development viewpoint, promoting economic and social growth in Shandong Province should be built on efficient resource exploitation and green and low-carbon development. There is a lot of HDR waiting to be discovered, developed, and used so that we may have reliable sources of green, low-carbon energy and keep the economy growing sustainably.

The geothermal sector has had significant growth in recent years, and as a great resource, the HDR is certain to have a substantial amount of development space. The exploration of HDR geothermal resources contributes to the diversification of the energy business. It can also give valuable theoretical and practical knowledge for developing and utilizing other types of geothermal resources.

2. CURRENT SITUATION AND ZONING OF REGIONAL GEOTHERMAL DEVELOPMENT IN SHANDONG PROVINCE

Shandong Province is located in the high heat flow zone on the west coast of the Pacific Ocean, at the collision zone between the North China plate and the Yangtze plate, and at the confluence of the North China Depression and the central Shandong Uplift, with a highly developed structure. Since the Mesozoic and Cenozoic, significant magmatic activity in Shandong has been accompanied by severe fault block movement and the widening of the continental rift. The following are geothermal formation, heat conduction anomalies, and hydrothermal activity anomalies. Shandong has strata from the Archean to the Cenozoic periods, and each stratum is well-formed. Mesozoic and Cenozoic strata predominate in the Shandong area, followed by Paleozoic strata. The distribution of Proterozoic strata is confined, while Archaean strata are widespread. The stratum outcrop area increases successively from older to younger strata (Zhang et al., 2011; Zhang et al., 2014). The Jimo fault separates the first-order structural units of Shandong Province in Muping, Wulian, and Changyi Dadian in the Yishu fault zone, which belong to the North China plate in the northwest and the Sulu orogenic belt in the southeast. The second-order structural units are separated into the Luxi uplift area, the North China depression area, the Jiao-Liao uplift area (Lulong uplift area), the Jiaonan-Weihai uplift area, and the North Jiangsu uplift area by the Yishu fault zone, the Qihe-Guanggrao fault, the Liaocheng-Lankao fault, and the Muping-Jimo-Wulian fault. Tertiary tectonic units are delimited by substantial regional faults (Xu et al., 2021). In addition, based on geothermal geological data, lithology, rock heat generation rate, rock thermal conductivity, geothermal gradient, and other data of Shandong Province, Shandong Province is divided into four regions, namely eastern Shandong, northwestern Shandong, Yishu Fault zone, and south-central Shandong, as depicted in Fig. 1 (Revised from Xu et al., 2021).

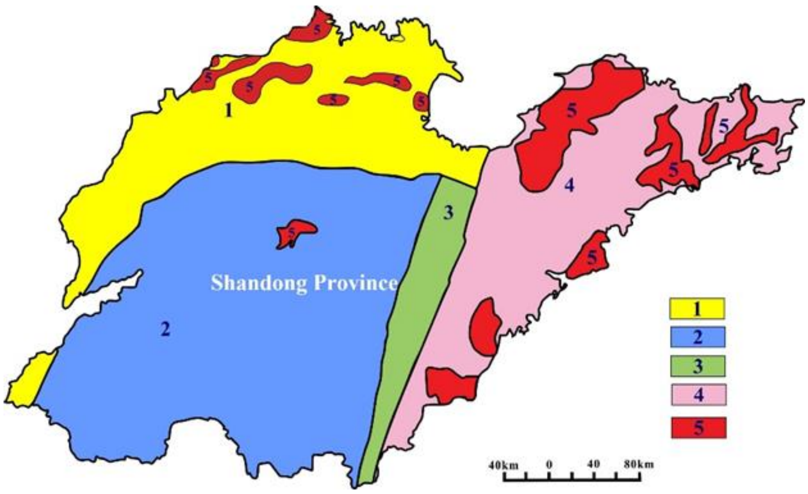

Fig.1 Estimation map of geothermal resources in HDR in Shandong Province (1. Northwest Shandong; 2. Central and southern Shandong; 3. Yishu fault zone region; 4. Ludong region; 5. Key exploration areas for HDR) (Revised from Xu et al., 2021)

Magmatic activity is very frequent in Shandong Province. Except for the volcanic activity in Mesoarchean, Neoarchean, Mesozoic, and Cenozoic, the other geological ages are dominated by magmatic intrusion. Magmatic rocks are widely distributed, with an outcropping area of 30976 km^2, accounting for about 20% of the province's land area (Song et al., 2012). Up to now, 17 cities in the province have found geothermal resources, natural hot springs, and artificial exposed geothermal in more than 800 places, and the water temperature is between 40 and 90℃ (Xu et al. 2014). Furthermore, Shandong province is located in mainland China's eastern coastal Pacific tectonic domain. Since the Miocene, the neotectonic movements have been intense and complex in form. According to the locations of hot springs, more than 90% of hot springs in Shandong Province have emerged in the neotectonic uplift area. The characteristics of tectonic setting, volcanic activity, neotectonic movement, and heat conduction in Shandong Province have created geological conditions for the occurrence of HDR resources in Shandong Province (Xu et al., 2021).

3 THE CHENZHUANG LATENT UPLIFT AREA IN LIJIN COUNTY

3.1 Geological tectonic setting

The Chenzhuang latent uplift area is mainly located in Chenzhuang Town and Yanwo Town of Lijin County, and it is a part of the North China Plate, North China Depression, Jiyang Depression, and Zhanhua latent fault depression in terms of tectonic units. According to the "Lijin County HDR survey" and the comprehensive analysis of oil drilling results in the area, it is known that the area with granite distributed in the buried depth of more than 4000 m is Chenzhuang latent uplift area. Chenzhuang subduction uplift area is Zhanhua subduction in the north and west and Dongying subduction in the south and east, showing a nearly east-west rectangular distribution (Fig. 2). The uplift is 63 km long from east to west and 15 km wide from north to south, covering an area of 558.3 km^2. The Neogene and Quaternary strata in the uplift area cover 950-1900 m, and the lower part is composed of Neoarchean Taishan Group intrusive rocks and Paleozoic strata (Wang et al., 2015).

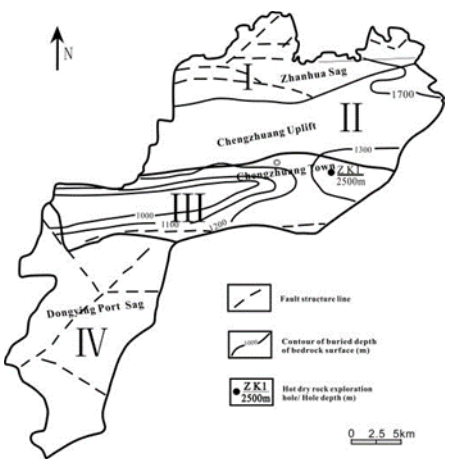

Fig.2. Tectonic structure and bedrock buried-depth contour map at Chenzhuang uplift (Revised from Wang et al., 2015)

3.2 Stratigraphic lithology in the study area

The strata in the Chenzhuang subduction uplift area change greatly. In particular, under the influence of the Yanshanian and Himalayan movements since the Mesozoic, thick Cenozoic strata were deposited on it, and the thickness of the strata varied greatly. The thickness of Neogene and Quaternary strata is 950-1900 m. The strata in the area from old to new include: 1) Neoarchean Taishan

Group ($A_{r3}T$); 2) Paleozoic (P_z) Cambrian -- Ordovician (∈-O); 3) Shahejie Formation and Dongying Formation in Paleogene; 4) Neogene Guantao Formation and Minghuazhen Formation; 5) Quaternary System (Tan et al., 2015).

Strata uncovered by the GRY1 hole located on the west side of Qianguo Village, Chenzhuang Town, are successive: Quaternary Pingyuan Formation (275 m), Neogene Minghuazhen Formation (275- 989 m), Neogene Guantao Formation (989 - 1243 m) and Neoarchean Taishan Group (1243-2500 m). The division of stratigraphic boundaries is shown in Tab. 1 (Revised from Wang et al., 2016).

Tab. 1 Stratigraphic boundary division (Revised from Wang et al., 2016).

Stratigraphic age	Bottom boundary buried depth /m	Lithologic characteristics
Quaternary plain Formation	275	Light brown yellow, light green, gray sandy clay, clay with clay siltstone
The Minghuazhen Formation of Neogene	989	The sediment is fine-grained, mainly composed of gray-green and brown-red mudstone, interspersed with gray-white sandstone, fine sandstone, and siltstone. Gray-green stripes and patches are developed in brown and red mudstone, and sometimes gypsum wafers are developed in mudstone
The Neogene Guantao Formation	1243	The lithology of the lower section is gray-white, and gray thick-bedded massive conglomerate, pebbled sandstone, sandy conglomerate, fine sandstone with gray-green siltstone, brown, red mudstone, sandy mudstone, and quartz and chert conglomerate are generally developed at the bottom
The Neoarchean Taishan Group	2500	The lithology of the upper section is basalt and a small amount of intrusive granite. The lithology of the lower section is gabbro and intrusive granite metamorphic rock series

3.3 Research on geothermal geological resources of HDR in the Chenzhuang Latent uplift area

In 2011, the Second Hydrogeology Engineering Geology Brigade of Shandong Provincial Bureau of Geology and Mineral Resources conducted a resource survey of HDR (well DR1) in Lijin County. The project has done much work from target site selection, a physical exploration well, HDR conceptual model establishment, HDR drilling verification, comprehensive logging, core sampling, radioactive testing analysis and evaluation, target layer fracturing test, pre-fracturing, and post-fracturing pumping and water injection test, HDR geothermal resources estimation and so on. It is the first project to investigate and evaluate HDR geothermal resources in China systematically (Tan et al., 2020). The radioactive elements in the medium acidic rock mass will generate heat when they decay. It is generally believed that "only the radioactive isotopes with a half-life similar to the age of the earth, such as U, Th, and K, will generate a large amount of heat during the decay process, constituting the main heat source of the earth's internal heat (Wang, 2016; Lin et al.,2016; Kang et al., 2020). At present, "the heat contribution of the heat-generating element U and Th on Earth is close to each other, accounting for 40%", while the heat contribution of the heat-generating element K is relatively small, accounting for only about 20%, as shown in Fig. 3 (Revised from Arevalo et al., 2009). The heat source type of HDR in this study area is also mainly generated by radioactive elements. Combined with the heat storage structure of this area, a favorable prospect area of HDR geothermal resources is formed.

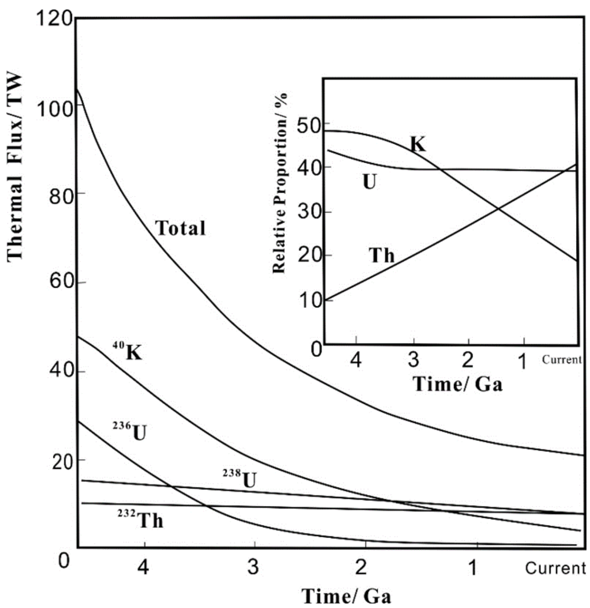

Fig. 3. Heat contribution and time variation curve of heat-generating elements (Revised from Arevalo et al., 2009)

Based on the brief introduction of the research status of HDR at home and abroad, Wang et al. analyzed the geothermal geological conditions of HDR in Lijin County, the heat storage characteristics of HDR, and the exploitation and utilization conditions, and estimated and calculated the number of resources. They suggested that, based on the previous investigation, we should continue to increase financial support to establish a demonstration base for HDR research. It will provide a test base for future research, development, and utilization of HDR resources and other related geoscience research. Radioactive elements mainly generate the heat source types of HDR in this study area. Combined with the heat storage structure in this area, a favorable prospect area of HDR geothermal resources is formed (Wang et al., 2015). In 2015, Tan et al. took the Chenzhuang latent uplift area of Shandong Province as an HDR exploration and research area, combined with the relevant basic data of HDR investigation based on the analysis of the earth heat flow and geothermal field in the area and calculated the radioactive heat generation rate of borehole rock by using Rybach heat generation rate formula. From the relation between the GRY1 hole and the depth, the overall value of the heat generation rate is larger, above 1650 m, and its amplitude is larger. The heat generation rate reaches 4.72-6.78 $\mu W/m^3$ at a depth of 1430-1645 m, mainly composed of biotite-bearing monzogranite and chlorophyllide monzogranite. The 1645-2500 m is mainly composed of granite, biotite-bearing diorite, and gabbro, and the heat generation rate decreases somewhat. Overall, granite's heat generation rate varies little, ranging from 2.0-2.5$\mu W/m^3$. However, the biotite and weak chlorite monzogranite have higher heat generation rates, and the change is great. Based on the comprehensive analysis of the geotectonic, lithology, and geothermal gradient of the Chenzhuang area in combination with borehole data, Wang et al. speculated that the Chenzhuang area has the condition of HDR below 3700 m and concluded that the Lijin area has good conditions for the development of HDR. After a series of studies, in 2020, Tan took Lijin HDR GRY1 hole as an example. It is believed that although its natural crack rate and permeability were poor, its permeability coefficient was greatly improved after hydraulic fracturing. The fracturing mode was a composite fracturing mode of artificial high pressure and natural crack, and a large amount of water injection could be obtained under controllable orifice pressure. It benefits the development and utilization of HDR resources. He also evaluated this area's HDR geothermal resource reserves. The thermal resources contained in HDR within the buried depth of 5000 m in Chenzhuang latent uplift area is 2.654×10^{20}J, equivalent to 9.021 billion tons of standard coal. The amount of available resources is 5.29×10^{18}J, equivalent to 180.4 million tons of standard coal. In addition, he believes that many key technologies are involved in the investigation and evaluation of HDR geothermal resources, and standardization is conducive to guiding the subsequent development and utilization of HDR geothermal resources. Relevant technical requirements and regulations of HDR geological exploration should be issued as soon as possible (Tan et al., 2020).

4. TECTONIC ACTIVE BELT IN WENDENG AREA

4.1 Geological tectonic setting

The Shandong Peninsula is located in the easternmost part of Shandong Province, and its administrative area is composed of Qingdao, Yantai, and Weihai. It starts from the Jiaolai River and Jiaozhou in the west, extends to Weihai and Rongcheng in the east, extends from Longkou and Penglai in the north, and reaches Qingdao in the south. Its geographical coordinates are 119°28'-122°43' east longitude and 35°33'-37°50' north latitude, covering an area of 29830 km^2. The western part of the work area is Jiaolai Basin, and the rest of the area is a typical middle-low hilly area with large relief. Most of the areas are between 100-300 m above sea level. The terrain is generally higher inland and lower offshore. Jiaodong area belongs to the peninsula marginal water system with short sources and fast flow, most of which flow into the sea alone. The seasons greatly affect the flow, and there is a great disparity between abundance and dryness (Zhao, 2019).

Wendeng is in front of the Pacific plate subduction east of the Shandong Peninsula. The regional tectonic plate is located in the Weihai-Rongcheng uplift of the Sulu orogenic belt. The buried depth of the Moho surface is 30-32 km, and the earth's heat flow value is 70-85.4mW/m^2 (Li and Sun, 1997). The Wendeng (super-unit) granites were formed in the Mesozoic Jurassic (early Yanshanian), mainly composed of the monzogranite with different particle sizes, which invaded the Neoproterozoic orogenic sequence and became a set of acid granites, marking the beginning of lithosphere thinning in eastern China (Wang et al., 2012).

According to the study results, geothermal resources are abundant in the Wendeng region. There are five recognized natural hot springs in the Wendeng region. Using the geochemical temperature scale, the thermal reservoir temperature is calculated to be 85 °C-180 °C. The water temperature ranges from 52 °C to 72 °C (Luan and Liu, 2003; Luan et al., 2002). This region is situated on the eastern edge of the Rushan-Weihai complex anticline, and most of the regional fault system strikes northeast. Second, the ductile shear zone is extensively developed in this region, establishing a shear zone-type dynamic mineralization model, and the natural hot spring in the Wendeng region is connected to the tension-torsion zone's deep and ductile shear zone. During the early Yanshanian epoch of the Mesozoic, the tectonic activity in this region was intense and extensive, resulting in the formation of fault systems that provided a conduit for the transport of subsurface heat sources. In addition, the great thermal conductivity of granite created ideal circumstances for creating hot springs by facilitating the conduction of deep heat sources. In conclusion, deep and huge faults influence the creation and development of geothermal in this region, and the development features of deep fault structures must be investigated to investigate the deep high-temperature rock mass.

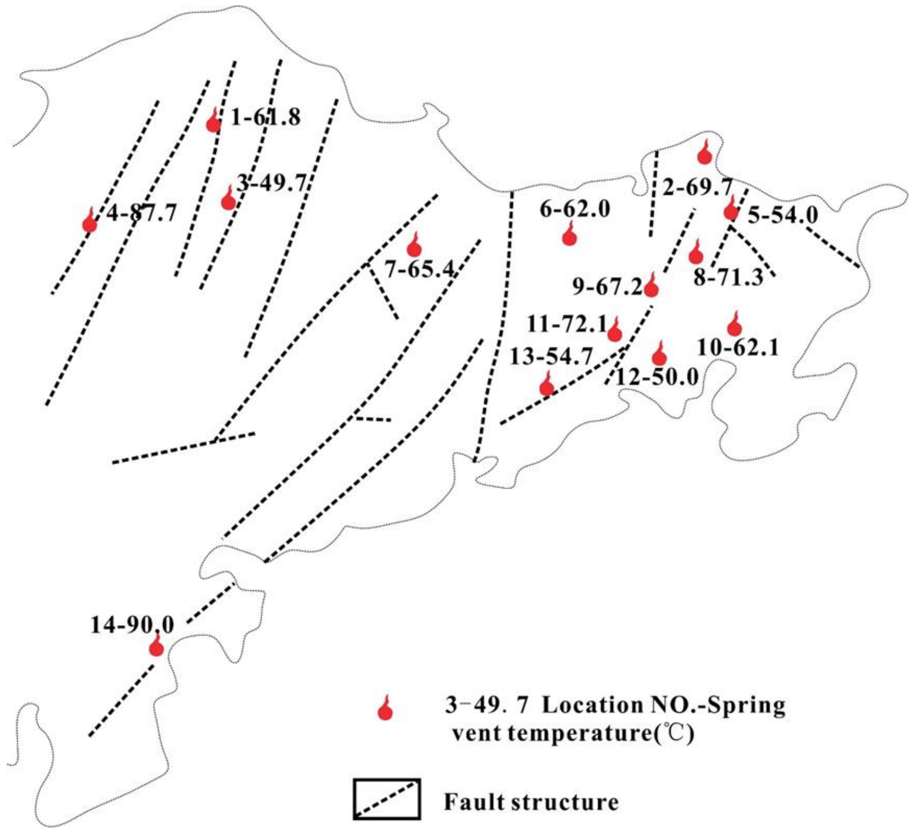

Fig.4. Distribution of hot springs in Jiaodong (1.Penglai Wenshi Decoction; 2. Weihai Baoquan Soup; 3. Qixia Aishan Decoction; 4. Zhaoyuan Tang Dongquan; 5. Weihai Hot Spring Soup; 6. Muping Longquan Soup; 7. Yu Jia Tang; 8. Wendeng Hongshui LAN Tang; 9. Wenden Qili Soup; 10. Wenden Hullei Tang; 11. Wenden British Soup; 12. Wenden Bei Tang; 13. Rushan Xiaotang; 14. Jimedong Hot Spring) (Revised from Zhao, 2019)

4.2 Stratigraphic lithology in the study area

The intrusions in the Shandong Peninsula are well developed, mainly composed of Neoproterozoic granitic gneiss and Mesozoic granites. The Wendeng granite is mainly composed of two large complex plutonic plutons, the Wendeng complex, and the Lujiahe complex, which are distributed in an elliptical shape near the south-north and an irregular band near the east-west, respectively. The main lithology is monzogranite with various structures (fine-grained porphyritic, medium-grained porphyritic, coarse-grained porphyritic, and the excessive structure between them), and the intrusion age is about 160 Ma. Several hot springs, such as Baoquan Hot Spring, Wenquan Hot Spring, Hongshuilan Hot Spring, and Qili Hot Spring, are exposed near the Wendeng Granite rock mass with a large flow. Currently, most of them are used for physiotherapy baths. According to the statistics in 2017, the daily mining volume of several hot springs is about 10,000 m^3. The analysis shows that the regional fault or intrusion contact zone communicates the heat of deep HDR, and shallow cool water infiltrates and is heated rapidly. The existence of deep HDR mass is closely related to the formation of hot springs in this area. Therefore, the Wendeng rock mass is the focus of HDR resources investigation in the Shandong Peninsula (Zhao, 2019).

4.3 Study on geothermal geological resources of HDR in Wendeng Area

Currently, restricted by development technology and mining means, HDR resources refer to the hot rock mass with shallow burial depth, high temperature, and economic development value (> 180 ℃). The most potential areas for developing and utilizing HDR are concentrated in the new volcanic activity area, crust thinning area or deep tectonic development area. The Wendeng pluton was formed in the Jurassic period of the early Yanshanian period, and the formation of geothermal energy is related to the high earth heat flow value and deep fault structure in this area. In order to further explore the deep geothermal resources in the Wendeng area and detect the deep development characteristics of the heat-controlling structure, magnetotelluric detection technology was adopted. The distribution law of heat-controlling structure was speculated and verified by studying the deep electrical structure, and a one-glance temperature hole was successfully implemented. According to the drilling data, four anomaly zones of the geothermal gradient were found in the fracture zone. The MT method detects and studies the development law of heat-controlled deep and large faults and provides an important reference value for further research on HDR (Zhao, 2019). The HDR borehole location was determined by magnetotelluric and controlled source exploration based on the study area's geological, geophysical, and geothermal geological data. Through drilling, logging, coring, and rock and ore analysis tests, the scale of deep Wendeng granite, the spatial distribution of fractured reservoir, deep geothermal temperature and geothermal gradient, granite thermal physical parameters, and rock mechanics parameters are obtained comprehensively. A three-dimensional geological model of HDR is established, and its power generation capacity is analyzed by numerical simulation. In the study area, intrusive rocks and tectonic faults are developed, the earth heat flow value is 48-85 mW/m^2, and the geothermal gradient in the geothermal anomaly area is 5.3- 18.59 ℃/100m, indicating that Wen and other areas have excellent conditions for the occurrence of deep geothermal energy.

5. PROBLEMS AND PROSPECTS OF GEOTHERMAL GEOLOGICAL RESOURCES IN HDR IN SHANDONG PROVINCE

5.1 Existing Problems

The geothermal resources of HDR have huge reserves and less pollution in the energy development process, which is regarded as one of the pillars of future energy. Compared with the technology formed abroad, HDR's development is still in its initial stage. The reasons for this phenomenon are as follows.

1) Occurrence characteristics and mining conditions: HDR resources' occurrence characteristics and mining conditions are the basis for developing and utilizing HDR resources. It is necessary to do a good job in the investigation and evaluation of HDR resources and the research and development of key mining technology systems and establish the corresponding database.

2) Earthquake: Although HDR geothermal geological resources belong to clean energy, in the case of unreasonable evaluation of recoverable resources and improper development technology, it will still cause certain environmental impacts. The main environmental impact of the ground source heat pump project is the decrease of groundwater level and the subsequent heat accumulation and cold accumulation. The main environmental problem in the development and utilization of HDR is the impact of micro-earthquake on the surrounding residents.

3) Drilling technology and equipment: Because developing geothermal resources in HDR requires deep drilling, the heat resistance temperature of the drill bit in the construction of a high-temperature rock power generation well needs to reach 350℃. In addition, anti-inclination drilling technology needs to be applied in the actual work, which increases the difficulty and production cost in the development process. High cost has become a problem in HDR development. Therefore, more efforts should be made in fracturing drilling technology.

4) Fracturing technology and connectivity: Fracturing technology must be used in HDR applications to create cracks in tight, impervious rock masses and allow connectivity between Wells. Connecting Wells is complex and difficult to solve and needs further study.

5) Implementation: As mentioned earlier, HDR has great heat storage in the 3-10 km range. Nevertheless, many scholars and experts think that as a kind of geothermal resource, HDR power generation will face the same predicament as conventional geothermal power generation. At present, geothermal heating and heating water are developing rapidly in China, but the use of geothermal power generation has been stagnant.

5.2 Prospect

Shandong Province's HDR geothermal resources may be developed and used to successfully assist the creation of a clean energy demonstration province and significantly improve the supply and production of clean energy in Shandong Province via grid-connected power generation. At the same time, both the production and consumption of fossil energy can be greatly reduced, helping to play a positive role in the protection of the ecological environment by slowing or stopping the devastation of natural resources like forests, grasslands, and wetlands that are caused by the exploitation of fossil energy. It provides a firm basis for future HDR industrialization and the creation of HDR demonstration locations. Meanwhile, the development and utilization of green and low-carbon energy, the advancement of science and technology in the exploration of deep geothermal resources, the revolution in energy production and consumption, and the green and sustainable development of society are all facilitated by the exploitation and utilization of HDR geothermal geological resources.

More HDR research teams will actively explore and develop HDR technology as the market grows, which is dependent on new discoveries. The main technologies of HDR are continually pushed to achieve breakthroughs, and the commercial development process of HDR will enter a fast lane, thanks to the collaborative invention of people from all walks of life. Predictions indicate that HDR technology will soon see significant advances in research and use. Once HDR technology and its use become commercialized, the industry will benefit enormously from the influx of investment and new ideas.

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