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Progress and Prospect of Hot Dry Rock Exploration and Development in China

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ABSTRACT

The exploitation and utilization of clean energy is a resource and environmental issue of common concern for global sustainable development. As a vital strategic and sustainable future energy, hot dry rock (HDR) has attracted more and more attention. Since 2012, the China Geological Survey has organized and implemented the nationwide terrestrial HDR resources survey, evaluation, exploration, and development, and significant stage progress has been achieved. A series of fundamental maps have been compiled, such as terrestrial heat flow value, curie surface depth, distribution of acidic rock, and heat-controlling structure in China. The resource potential of terrestrial HDR in China has been preliminarily estimated and provided a sounding basis for the target site selection. HDR exploration and evaluation have been carried out in typical areas of Qinghai, Shandong, Hebei, Shanxi, and Jiangsu provinces, and a breakthrough has been achieved in the Gonghe Basin of Qinghai. The first HDR exploration and production demonstration project in China was carried out in Gonghe, Qinghai Province, which made a series of meaningful outcomes in deep HDR exploration, high-temperature hard rock drilling, large-scale reservoir stimulation, reservoir connectivity and flow circulation, organic Rankine cycle (ORC) power generation, etc. China will continue to promote the construction of the Qinghai Gonghe HDR Demonstration Project, intensify the exploration and development of HDR in eastern China, actively promote the industrialization of the exploration and development of HDR, and support the national strategy of achieving carbon peak and carbon neutrality.

1. PREFACE

HDR resources refer to the enormous energy resources that can be utilized by current technology in the high temperature (≥180℃) rock mass which is buried deep and does not contain or contains only a little fluid. The HDR is an ideal sustainable green energy in the future due to its wide distribution, can be used as baseload energy, can be transported without storage, and has less land occupation (Jiang et al., 2014). Los Alamos National Laboratory of the United States started the HDR exploration and development research in Fenton Hill, New Mexico, in the 1970s. After more than 50 years of continuous exploration, significant progress has been made in theoretical research and engineering development practice. The prospect of HDR resource development is further evident, and more and more countries have joined the ranks of HDR exploration and development (Breede et al., 2013; Lu, 2018). The HDR exploration and development started relatively late in China. Its successful implementation will significantly change traditional energy structures and promote ecological civilization construction in China.

Since 2012, the China Geological Survey (CGS) and other relevant units have explored HDR resources in Qinghai, Fujian, Guangdong, Shandong, Hebei, Shanxi, Jiangsu, and Hainan, discovered several high-temperature geothermal resources and assessed the potential of terrestrial HDR resources in China. In addition, high-temperature HDR exceeding 200℃ was found at 4000 meters in Gonghe Basin, Qinghai Province. In 2019, China Geological Survey (CGS) launched China's first HDR resources exploration and production demonstration project in Qiabuqia, Qinghai Province. After three years of effort, the experimental HDR electricity generation and grid connection was successfully realized in 2021, promoting substantial progress in HDR exploration and development in China. A series of key technological breakthroughs have been made, such as deep HDR exploration, high-temperature hard rock drilling, large-scale reservoir construction, reservoir connectivity, and flow circulation.

Based on summarizing the global progress of HDR exploration and development, this paper aims to provide some thoughts on the future research direction of China and put forward the prospect of exploitation and utilization.

2. DEVELOPMENT PROGRESS OF HOT AND DRY ROCK IN THE WORLD

HDR power generation is the frontier of the world's new energy exploration, and the number of HDR development projects (EGS projects) around the world is increasing. Up till now, 64 EGS projects have been built in the United States, the United Kingdom, Germany, France, Australia, Switzerland, Sweden, Japan, China, and other countries. However, many projects have been halted because of restrictions such as earthquakes, drilling, or power plant operations, and only 29 are still operating.

In recent years, with the increasing global energy demand, developed countries gradually strengthened the exploration of HDR exploitation and utilization. Funded by the U.S. Energy Administration, the U.S. Geological Survey (USGS) completed four national geothermal resource potential evaluation rounds in 1975, 1978, 1982, and 2008. According to the latest assessment results in 2008, the HDR resource potential in the United States is 517,800 MW. In 2019, the United States launched the FORGE project (Frontier Observatory for Research in a Geothermal Energy), aiming to achieve commercial development of EGS through crucial technology research and development, and making HDR a representative of clean, reliable, flexible, and renewable energy. The project aims to generate more than 100,000 megawatts of electricity by 2050, an increase of nearly 100 times compared to the current hydropower generation, to provide green electricity for 100 million homes in the United States.

In general, the current EGS project is still in the experimental stage. Its commercial development still faces many challenges in theory, technology, capital, policy, and public acceptance, among which the fundamental theoretical breakthroughs in geophysical detection of heat storage, resource evaluation, efficient artificial cracking, and induced earthquake prevention and control are the premise of realizing the industrialization of HDR development.

3. PROGRESS OF HDR EXPLORATION IN CHINA

3.1 HDR exploration and development projects.

3.1.1 From 2011 to 2015

During the 12th Five-Year Plan Period (2011-2015), the CGS organized the HDR resources assessment, revised the heat flow map, and drew the maps of curie surface depth, the acidic magmatic rock mass distribution, the thermal control structure map, and typical profiles, which reflect the deep tectonic pattern and the variation law of deep lithosphere geothermal gradient, as well as the relationship between heat sources and neotectonics in terrestrial area of China. The temperature at different depths was estimated based on the analysis of terrestrial heat flow, thermal conductivity, and heat generation rate of rocks at different depths, and the thickness of the radioactive element concentration layer. And based on this, the potential of HDR resources was estimated by the volumetric method, and the resource base of HDR resources in China was preliminarily identified. The results show that the HDR resources buried at 3-10 km depth in terrestrial are of China are about 2.5×10^{25} J (equivalent to 856 trillion tons of standard coal). Among them, the resources buried above a depth of 5.5 kilometers are about 3.1×10^{24} J (equivalent to 106 trillion tons of standard coal). China has 188.6 billion tons of proven, directly usable coal reserves. (China Geological Survey, 2018; Wang Guiling,2017; Lin Wenjing et al., 2012; Ma Feng et al., 2015).

3.1.2 From 2016 to 2022

During the 13th Five-Year Plan period (2016-2020), based on the investigation and evaluation, the HDR exploration in Gonghe, Qinghai Province, southeast coastal areas, northern Jiangsu Basin, Datong Basin, and other typical areas was carried out, and many breakthroughs were made (Lin Wenjing, 2021).

Through regional geothermal geological survey and comprehensive geophysical exploration in Gonghe Basin, Qinghai Province, favorable target areas for HDR exploration and development have been delineated (Zhang Senqi, 2020; Zhang Senqi, 2021). The GR1 exploration well successfully discovered HDR mass with a temperature over 200℃ at a depth of 3,705 meters, achieving a breakthrough in HDR exploration. A preliminary evaluation of the amount of HDR resources in the Gonghe Basin above 5 km is equivalent to about 84.5 billion tons of standard coal. Based on comprehensive physical and drilling data, eight favorable areas for HDR exploration and development were delineated, and one target area for HDR exploration and development was screened out. Since 2018, several technologies have been systematically developed, such as HDR exploration, drilling, storage, monitoring, numerical simulation, resource evaluation, efficient power generation, expansion, and efficiency enhancement. More than 30 critical technical equipment and more than 300 technical processes had been completed in 6 aspects, including exploration and evaluation, efficient drilling, safe storage, cyclic connected heat recovery, reservoir monitoring and evaluation, and efficient power generation. The geological survey and geophysical exploration of HDR were carried out, and three projects of HDR injection-production test in high-temperature hard rock were completed, two of which are directional wells. A high-precision monitoring system for microseismic and induced earthquakes was constructed. Through large-scale reservoir construction and cyclic injection production, the first experimental power generation of HDR in China was realized. The whole process technology system of HDR exploration and development was preliminarily established.

A 127.7℃ high-temperature hydrothermal resource was discovered at 3009 m in Huizhou, Guangdong Province, and the lower anhydrous section has the HDR resources potential. The well temperature measured at 3150 meters in Xuwen County of Leizhou Peninsula is 146.4℃, and the conjectural temperature can reach 180℃ at 4000m. A high-temperature heat reservoir exceeding 185℃ was detected at a depth of 4,387 meters in the Fushan area, northern Qiongqi Province. In Xinghua City, northern Jiangsu Basin, a geothermal exploration well was conducted at a depth of 4701.68 meters, and the temperature was 155℃. In Tianzhen County, Shanxi Province, the high temperature and high-pressure geothermal fluid was detected at a depth of 1624 m. The wellhead fluid temperature reached 160.2℃, and the associated HDR resources have great potential. An Archean heat reservoir with a temperature of 150℃ was drilled at a depth of 3965 m in Matouying, Tangshan, Hebei Province, which has a good demonstration significance for the exploration of hot and dry rock resources in the Beijing-Tianjin-Hebei region. Datong of Shanxi, Matouying of Hebei, Xinghua of Jiangsu and other places have successively carried out dry-hot rock exploration and experimental power generation under different geological conditions.

3.2 Progress of science and technology in HDR exploration and development.

Since2013, The Ministry of Science and Technology, the National Natural Science Foundation of the People's Republic of China and the China Geological Survey have set up special projects to carry out research on the mechanism related to the exploration and development of dry-hot rocks in China.The high temperature-resistant material tools suitable for HDR development were developed, and the high-performance equipment .High temperature resistant and environmentally friendly drilling fluid, fracturing temporary plugging agent, crosslinking fluid, and other materials were developed. High temperature-resistant combined turbodrill, high-efficiency composite coring tool, high-efficiency directional coring tool, high temperature-resistant hard rock air DTH hammer bit, high-temperature resistant packer, and other tools were developed. Wireless MWD, high temperature resistant near-bit engineering parameter measuring instrument, drilling fluid forced cooling system, high sensitivity microseismic monitoring, organic Rankine power generation, and other equipment.

4. GREAT PROGRESS IN HDR EXPLORATION AND TRIAL PRODUCTION IN GONGHE, QINGHAI PROVINCE

Since 2018, China Geological Survey (CGS), together with Qinghai Provincial People's Government, has organized a scientific and technological battle for the HDR exploration and trial mining in Gonghe, Qinghai Province, and substantial progress has been made in exploration and exploitation theory, technology, and equipment. Three 4,000-meter-deep HDR trial mining wells have been completed, and the first large-scale HDR reservoir construction in China has been successfully implemented. Inter-well connectivity and grid-connected experimental power generation were realized in 2021.

4.1 Key technologies, including efficient and rapid drilling and multi-target directional drilling of high-temperature hard rock were explored, and three HDR test mining well group were completed in the Gonghe Basin, Qinghai Province.

To overcome the drilling difficulties of hard, high temperature, and high accident rate in HDR formation, a series of efficient drilling technologies and downhole tools such as a wireless inclinometer while drilling at 175℃, high-temperature resistant polymer drilling fluid system, drilling fluid forced cooling device, hydraulic impact rotary drilling tool, all-metal high-temperature resistant turbine drilling tools have been developed and applied on site, which forms a set of efficient and safe directional drilling technology for hot and dry rock with controlled wellbore trajectory.

The 4000 m directional drilling was completed with a target error of 1.53-6.85 m, a single run of granite footage of 176.29 m, and a continuous directional drilling of over 700 m at 175℃. In addition, a set of air down-the-hole hammer drilling technology for HDR drilling is formed, which forms the technology and equipment reserve for the large-scale development of HDR with high-temperature resistance.

Figure 1: HDR Directional drilling site in Gonghe, Qinghai.

4.2 **Key technologies, including a low-risk reservoir-forming technology， the high ground stress heat reservoir efficiency enhancement and pressure reduction technology and inter-well connected circulation technology.**

<u>4.2.1 Construction and control of complex fracture network in HDR</u>

The parameters required for reservoir formation were comprehensively obtained through more than 300 experimental tests and 5 numerical simulation methods, and the fracture initiation and propagation mechanism was mastered. Through variable displacement, multi-liquidity, temporary plugging, and steering, the effective control of crack initiation and extension, crack direction, and extension distance was realized. And fracturing materials such as high temperature resistant temporary plugging agent, crosslinking fluid, and variable viscosity slick water was developed to support the fracturing process.

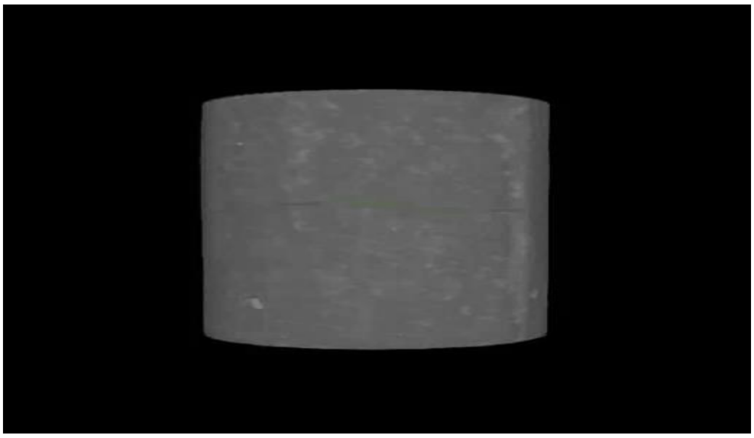

Figure 2: Multi-field coupling rock mechanics test of high energy accelerator CT.

4.2.2 The critical technology of inter-well connected circulation.

The problem of high ground stress and difficulty in injection and production of circulating well group in HDR reservoir had been overcome. Employing graded acidification, the acid injection process is optimized, the acid injection fracture system is adjusted, the acid liquid action distance is controlled, and the impedance between Wells is gradually improved. During acidizing, well-testing analysis and microseismic monitoring are synchronized, and reservoir evaluation and construction are interspersed with each other to realize the dynamic adjustment of the construction scheme to ensure the transformation effect. At the same time, through the interpretation and display of fracture intervals, the perforation position was accurately deployed, and the connectivity effect of injection-production wells was successfully enhanced by combining with reservoir reconstruction construction measures.

4.3 Key technologies, including directional control of HDR fractures, microseismic and time-frequency electromagnetic high-precision fracture joint real-time monitoring and interpretation had been formed independently.

4.3.1 High precision fracture real-time monitoring system

A high-precision microseismic data acquisition instrument and microseismic automatic positioning processing software were developed. A surface-shallow well-deep well microseismic monitoring system was innovatively constructed, and high-precision positioning methods such as double difference and migration stacking were adopted to obtain the spatial location and expansion trend of fractures in real-time.

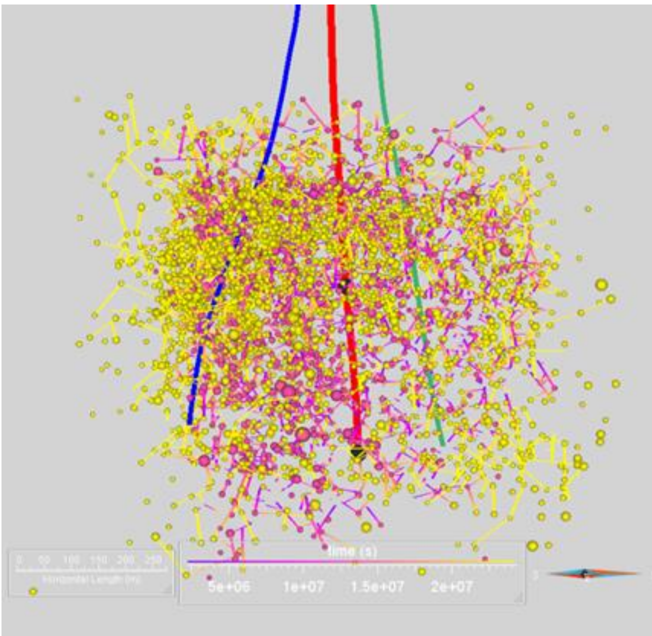

Figure3: Fracturing reconstruction volume of microseismic interpretation.

4.3.2 Imaging and evaluation techniques for reservoir construction

Based on the microseismic focal mechanism, the hydraulic fracture was reconstructed, the reservoir reconstruction volume was calculated by inverting the continuous fracture network, and the reservoir permeability was quantitatively evaluated. The high-power time-frequency electromagnetic method was successfully applied to monitoring HDR fracturing. The residual resistivity anomaly was inverted, and the fracturing fluid's spatial and temporal distribution was quantitatively evaluated based on the amplitude anomaly change.

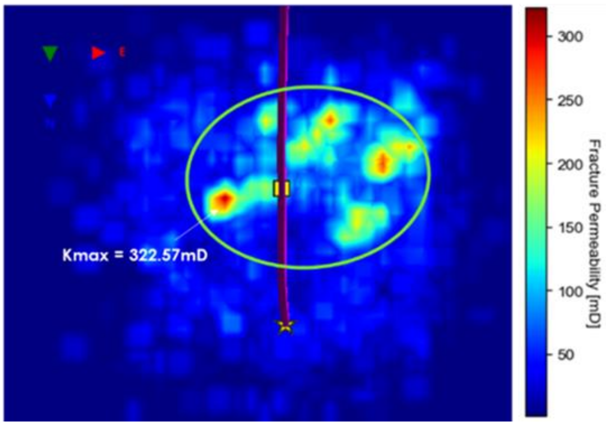

Figure4: Quantitative calculation of fracturing thermal reservoir permeability (x-z view).

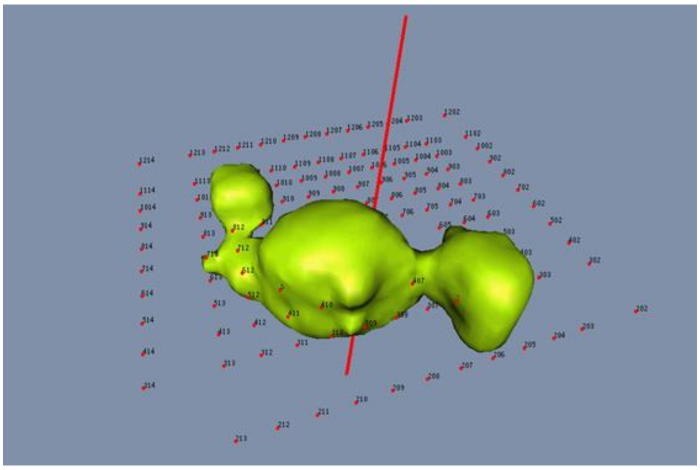

Figure 5: Time-frequency electromagnetic method to monitor the range of fracturing fluid.

Through the evaluation of fracture stress characteristics, combined with microseismic, well testing, tracer methods, and fracture thermal reservoir modeling and cyclic data fitting, a qualitative and quantitative analysis and evaluation process of thermal reservoir productivity were proposed to guide the stable cyclic heat recovery of thermal reservoirs. The connectivity of the fracture system was qualitatively evaluated by tracer test, and the fracture surface area and heat exchange area of the fractured reservoir was assessed according to the breakthrough curve.

4.4 The organic Rankine cycle power generation technology with independent intellectual property rights was developed, and the grid-connected power generation was realized.

An efficient and stable organic Rankine cycle generator set has been developed. The technology and equipment are self-controllable. The design efficiency is 13 % and can adapt to a wide range of 10-110 % working loads and heat source pressure of 10 MPa. The HDR series organic Rankine cycle power generation technology was studied, and the difficulties, such as high pressure of hot water and considerable load variation, were overcome. A multi-stage axial flow organic working medium expander was developed. The power generation equipment is independent and controllable, with a high degree of localization. In November 2021, the experimental power generation grid connection was successfully carried out.

4.5 The whole process of safe geological development and environmental monitoring control system of HDR engineering based on investigation, monitoring, evaluation, prediction, and control was established.

Through real-time monitoring of high-precision microseismic stations, fault risk assessment, seismic fortification capacity investigation of local buildings, monitoring, and evaluation of secondary microearthquake disasters and environmental impacts, an environmental impact monitoring network has been established for the exploration and development demonstration project of Gonghe in Qinghai Province. Thus, the induced earthquake evaluation and prediction technology, which takes the local environmental bearing capacity as the threshold, the fault mechanical stability evaluation as the basis, and the microseismic statistical analysis and model prediction as the combination, provides the safety guarantee for the HDR experimental power generation.

5. PROSPECTS FOR HDR EXPLORATION AND DEVELOPMENT

5.1 Geological survey

(1) Geothermal geological investigation and evaluation is the basis of geothermal energy exploration and development. With the attention paid to deep geothermal energy (HDR) buried more than 3000m, it is an inevitable trend to carry out a comprehensive investigation, evaluation, and exploitation of geothermal energy in the future. However, the tectonic system of China is complex, and there are still many fundamental geological problems, such as the distribution of HDR under different tectonic backgrounds,

heat control mechanisms, and accumulation mechanisms. It is necessary to establish a set of evaluation and management systems integrating 3D visualization geological models, multi-field coupling simulation, geothermal resources evaluation and prediction, engineering optimization design, resource allocation management, and so on.

(2) Geophysical exploration is the primary means of deep geothermal exploration. Transparency, 3D visualization, and quantification of exploration targets are the development trends of geophysical exploration technology. However, for deep geothermal resources and relatively complex geothermal systems, the theoretical understanding of the various characteristics of geological and geophysical responses of deep thermal reservoirs needs to be clarified, and the problem of multi-solution in high-temperature detection is prominent. It is still the frontier of global geothermal resources exploration technology to expand and explore the comprehensive deep geothermal exploration technology method containing multiple geophysical information such as heavy, magnetic, electric, and seismic. There is an urgent need to build geophysical exploration technology system for transparent and effective exploration of the deep geothermal geological structure, as well as critical technologies such as deep thermal storage temperature prediction and geophysical modeling.

5.2 Development and engineering technology

(1) HDR drilling and completion technology: Key technologies such as high-temperature measurement while drilling, high-temperature resistant long-life bit, bottom power drilling tool, high-temperature resistant drilling fluid, and cooling must be tackled.

(2) HDR reservoir construction technology: the fracture propagation mechanism of HDR is not clear, the fracture directional control technology of hot reservoir construction is not mature, high temperature resistant fracturing materials and long cycle injection equipment need to be developed and supported, and the mechanical mechanism between the cyclic injection and production and the rock is not precise.

(3) High-precision crack real-time monitoring and interpretation technology: high-precision microseismic data acquisition instrument needs to be developed, and automatic microseismic positioning and processing software needs to be finely developed. The high-precision positioning technology cannot meet the requirements of refined well layout design, and the real-time acquisition technology of fracture location and propagation trend needs to be studied.

(4) Evaluation of dry-hot rock reservoir reconstruction effect and fracture interpretation technology: micro-seismic fracture inversion, continuous fracture network inversion based on focal mechanism, and quantitative evaluation of reservoir permeability accuracy need more. Electromagnetic reservoir inversion, resistivity residual difference inversion method is still required, and quantitative assessment of fracturing fluid spatial and temporal distribution needs to be improved. Microseismic, well-test, and tracer methods cannot explain reservoir fracture. Fracture heat storage modeling and cycle data fitting.

(5) Mechanism and measures of earthquake prevention and control in HDR development: It is necessary to establish a forward-looking comprehensive magnitude prediction and control system based on the induced seismic mechanical mechanism and the vibration control mechanism with feedback regulation of wellhead pressure, total fluid volume, and hydraulic energy is still unclear.

5.3 Comprehensive Utilization

(1) Complementary utilization of multiple energy sources. Comprehensive utilization of multi-energy complementarity and complementary advantages should be combined with other forms of clean energy. Demonstration studies on geothermal power generation, geothermal drying, geothermal heating, geothermal bathing, geothermal greenhouse, geothermal aquaculture, and other engineering applications should be carried out according to the utilization sequence of HDR from high temperature to low temperature.

(2) Geological energy storage is a technology with geothermal as the core. The heat storage capacity of underground space and fluid can be found through detailed geothermal geological conditions investigation to select appropriate sites and store the heat generated by wind or solar energy in underground thermal reservoirs to achieve cross-time and space heat storage. Heat storage in summer and cold storage in winter, to perform pooled storage with wind, solar, and other resources. Using idle off-peak power to improve energy utilization rate is of great significance to the balance of power grid peak shifting and valley filling and is an important measure to absorb the abandonment of wind power and nuclear power.

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