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Prospective evaluation of dry-hot rock development and utilization in Bohai Bay Basin — understanding based on numerical simulation

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ABSTRACT

As one of the most promising clean and renewable energy sources, hot-dry rock is widely distributed and have high thermal storage temperatures. The Bohai Bay Basin, located in eastern North China, is a Middle-Cenozoic extensional rift basin formed under the background of North China Craton destruction. The measured geothermal heat flow data in the research area show that the heat flow in the area range from 44 to 106 $mW\cdot m^{-2}$, with an average of 66 $mW\cdot m^{-2}$, which is higher than the average heat flow in mainland China (61 $mW\cdot m^{-2}$). The geothermal temperature gradient in the study area, that is generally greater than 30°C/km is as high as 40-50°C/km in the uplift area. The geothermal temperature range in the research area is 180-226°C at a depth of 5000m, and the lithology is mainly metamorphic and igneous rocks, which has the conditions for the formation of hot-dry rock resources. In this study, the actual geothermal field parameters of the hot-dry rock favorable area in the Bohai Bay Basin were used to establish a hot-dry rock exploitation model with a layer thickness of 300m using COMSOL software to estimate the hot-dry rock resources of the thermal reservoir at a depth of 5000m in the research area. Based on the modeling of different well spacing and injection – production rates, the optimal solution was selected to calculate hot-dry rock resources. The results show that within 50 years, the average production temperature can be 163°C by the way of "two production wells and two injection wells" with well spacing of 400m and injection - production rate of 110m3/h. Under this scheme, the recoverable resources of the Bohai Bay Basin in 2000m×2000m range is 9.96×10^{14}J/a, equivalent to 3.40×10^{4}tons of standard coal, and the recoverable resources of the whole basin is 3.735×10^{20}J/a. According to the heat load index of 60-100W/m^2 per square meter of residential buildings, this exploitation scheme only needs 8000km^2 hot-dry rock field to meet the heating demand of residents in Beijing, which is less than the distribution range of deep hot-dry rock in Beijing. Therefore, the development and utilization of hot-dry rock in this study area can enhance the energy supply guarantee ability in North China and create a green low-carbon energy for sustainable development.

1. INTRODUCTION

In the context of global climate, environmental pollution and resource shortage, China is vigorously promoting 'carbon peak and carbon neutrality'. As a green, low-carbon, recyclable and renewable energy, hot-dry rock has the characteristics of large reserves, wide distribution, clean and environmental protection, strong stability, and broad prospects for development and utilization. The eastern part of China is close to the western Pacific high temperature geotropics. The Pacific subduction led to the extension of the eastern part of the Chinese Mainland to form ultra-thin lithosphere. The fault system is extremely developed, and there is strong volcanic activity, providing good geothermal geological conditions for high temperature geothermal resources. The Bohai Bay Basin where this area is located is an important oil and gas resource producing area in China. Through the exploration and research of many scholars and petroleum departments, it is shown that this area is rich in medium-high temperature geothermal resources. So far, the development and utilization of medium-high temperature geothermal resources in this area has begun to take shape, such as geothermal heating and cascade utilization in Xiong'an New Area, Tianjin and other places (Luo et al., 2021; Wang et al., 2017). However, there are few studies on the development and utilization of high-temperature geothermal resources, especially hot-dry rock resources. The hot-dry rock resources are located at a deep depth and high temperature, which leads to greater difficulties in development. Therefore, it is necessary to build a high permeability thermal reservoir manually. A simple hot-dry rock mining system is composed of an injection well, a production well and a fracturing network connecting the two wells. The drilling cost and later operation cost are high, so the production efficiency should be improved as long as possible during the development of hot-dry rock. The main factors affecting production are the well spacing of two wells, injection rate of injection wells, injection temperature, etc. Therefore, one of the most important tasks in the development and utilization of hot-dry rock is to find the optimal development plan. This study establishes a water-heat coupling model based on the geological data of the Bohai Bay Basin, analyzes the impact of different mining factors on the mining efficiency of hot-dry rock resources, to find the optimal plan and provide guidance for the hot-dry rock mining in the follow-up study area.

2. GEOLOGICAL AND GEOTHERMAL BACKGROUND OF THE STUDY AREA

Located in the east of North China, the Bohai Bay Basin is a Meso-Cenozoic extensional rift basin formed under the background of North China craton destruction, with an area of about $15\times10^{5}km^{2}$ (Liu et al., 2016). Its east and west sides are controlled by the NNE-trending Tanlu and Taihang Shandong deep and large fault zones, the northern part is the nearly EW trending Yanshan fold zone with relatively stable boundary conditions, and the southern part is limited by the Luxi uplift protruding in the NW direction, showing a regular rhombic geometric shape on the plane, as shown in Figure 1. The tectonic movement in this area is strong, with multiple structural layers, structural styles and deep and large faults developed. Since the Mesozoic era, volcanic activities have been widely distributed, and there have been multiple periods of basic rock intrusion and eruption activities, providing heat transmission channels and rich heat sources for geothermal resources (Dong et al., 2019; Wang et al, 2019; Jiang rt al., 2013). According to a large number of drilling and geophysical data, the strata in the basin are well developed, of which the thickness of the sedimentary layer is about 2-4km, which can be used as a good cap rock. The basement is the metamorphic rock series of the Archean Taishan Group, which can be used as a hot-dry rock reservoir (Zhang et al., 2020). The strong tectonic movement, moderate sedimentary thickness, and dense metamorphic rocks in the Bohai Bay area all laid the foundation for the formation of hot-dry rocks in the study area. According to the research of many scholars on the geothermal field in the Bohai Bay area, the heat flow value in some areas is relatively high, such as Jiyang Depression and Jizhong Depression, and the average heat flow value is about (65.8±5.4) mW/m^2 (Wang et al., 2013; Wang et al., 2020). According to Fig.2, the temperature in most areas of the Bohai Bay Basin is higher than 175 ℃ within 5000m of the buried depth of strata, basically reaching the limit of hot-dry rock temperature.

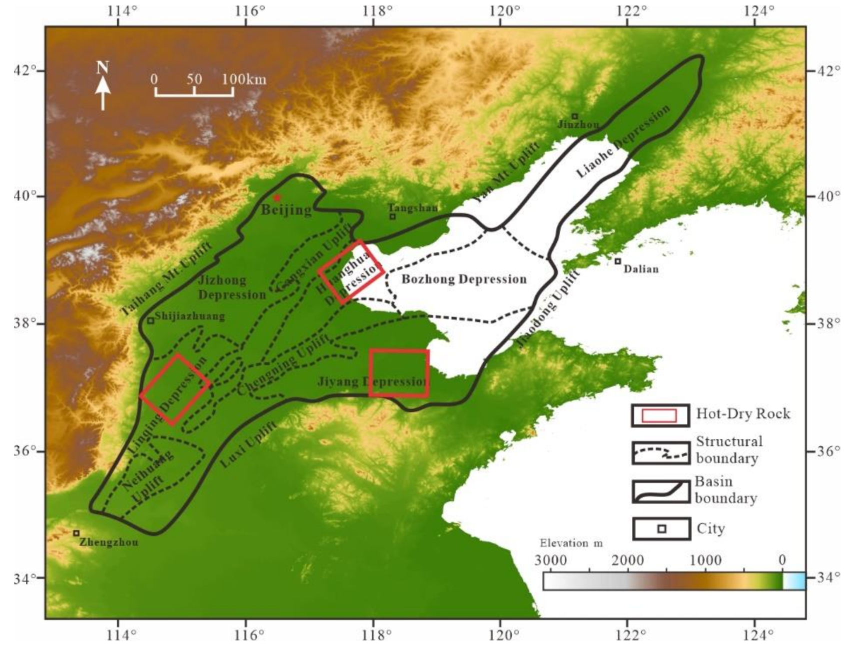

Figure 1: Location map showing the structural units of Bohai Bay basin (Jiang et al., 2016; Cui et al., 2022).

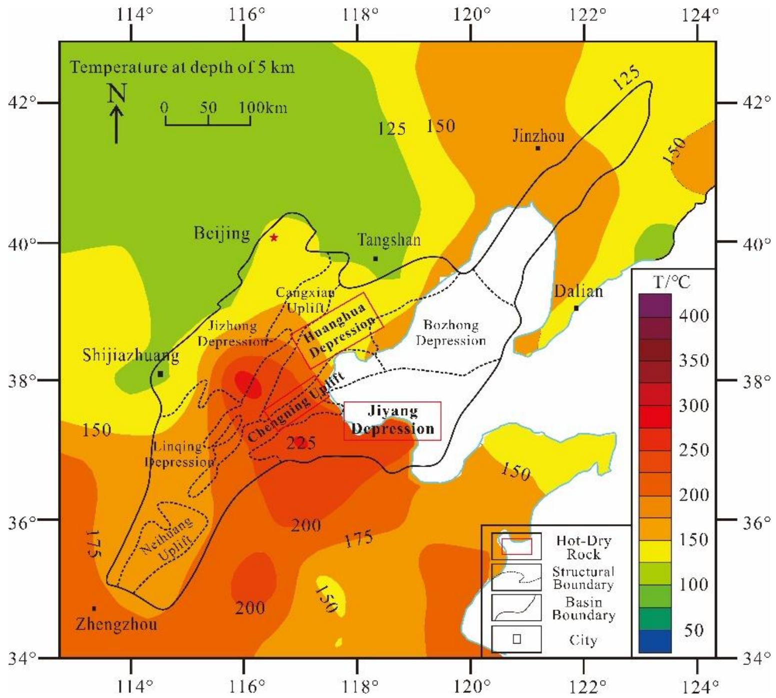

Figure 2: Temperature distribution map at 5000m depth in Bohai Bay Basin(Jiang et al, 2016).

3. OPTIMIZATION OF HOT-DRY ROCK EXPLOITATION SCHEMES

3.1 Establishment of mining concept model

In this study, the fracture system is regarded as a unit with thickness and the well is regarded as a line unit through the equivalent simulation method, and the thermal fluid coupling analysis and heat exchange between fractures are considered (Li, 2015). Use COMSOL Multiphysic to simulate the evolution of reservoir temperature and recovery rate of hot-dry rock under different mining conditions and years. The observation results seek the influence of different factors on the productivity of hot-dry rock. Since the simulation process focuses on the change of reservoir temperature, the model is divided into three layers, namely the top layer, the reservoir layer and the base layer. The development of hot-dry rock needs to increase the permeability of the reservoir to make the hydraulic connection between the injection well and the production well, which is reflected in the form of equivalent permeability layer in the geological model. Considering that the fracturing range of hot-dry rock development projects in Soultz France and Australia is less than or equal to 1km, the reservoir scale in this simulation area is set to 2km × 2km, which is large enough to avoid any boundary problems during the simulation process (Liao et al., 2015; Shaik et al., 2011). According to the temperature and pressure distribution conditions in the Bohai Bay basin, the thermal reservoir is located at 5000 buried depth. At present, the specified reservoir thickness for hot-dry rock development projects and hot-dry rock mining is usually set at 300m, which is still used in this simulation. The conceptual model is shown in the figure 3.

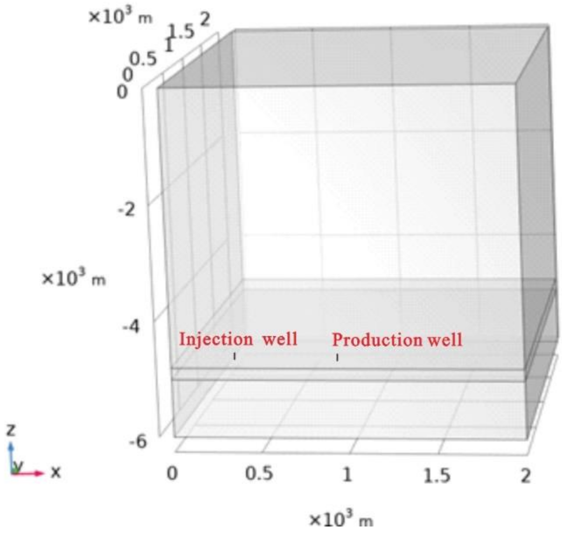

Figure 3: Conceptual model of the Enhanced Geothermal System and coordinate system.

3.2 Determination of physical field, parameters, and boundary conditions

In order to improve the stability of simulation results in the calculation process, the formation is considered as a porous medium with uniform porosity and permeability. The flow of fluid in the formation conforms to Darcy's law (Aliyu and Archer, 2021). The fluid loss rate is zero and there is no chemical reaction between the porous medium and the injected fluid. The heat transfer in rock follows Fourier's law. Darcy's law and porous medium heat transfer interface are used to calculate fluid movement and temperature distribution and change. The equation is as follows:

(1) Darcy's law equation

Darcy's law that defines the state of fluid flow in porous media indicates a linear relationship between the velocity field and the fluid pressure gradient. The formula is as follows:

$$v = -\frac{k}{\mu}(\nabla P - \rho_L g \nabla z) \tag{1}$$

Where k is permeability, μ is fluid viscosity, P is fluid pressure, g is gravity acceleration, and z is formation depth.

(2)Heat transfer simulation equation of porous media

Under this interface, the heat transfer is assumed to follow the local heat balance between the solid and liquid phases, that is, the solid temperature is approximately equal to the fluid temperature at a given depth in the system. The energy conservation in the fractured porous media of the formation is as follows:

$$(\rho \cdot C)_{eff}\frac{\partial T}{\partial t} + \rho_f \cdot C_{p,f} \cdot \mu \cdot \nabla T = \nabla \cdot \left(K_{eff} \cdot \nabla T\right) + Q \tag{2}$$

Where T is the temperature, Q is the heat generation rate, μ is the Darcy vector, r is the density, C is the effective heat capacity, K is the thermal conductivity, and ▽T is the temperature gradient. ρ_f is the fluid density, $C_{p,f}$ is the fluid heat capacity at constant pressure, K_{eff} is the effective thermal conductivity, $(\rho \cdot C)_{eff}$ is the effective heat capacity of porous media (Wang et al., 2021).

3.3 Simulation results

In order to explore the impact of different mining factors on the development potential of thermal reservoirs in the Bohai Bay Basin, a three-dimensional numerical model under the mode of 'Single Production-Injection' is established. Through the method of controlling variables, different well spacing schemes of 300-600m are selected for mining simulation. The simulation development time is 100 years. The simulation results show that (Fig 4) when the well spacing is too short, the heat exchange medium is not fully heated, and the production efficiency is low; When the well spacing is too long, the fracturing system cannot connect the injection well with the production well, and cannot achieve the production purpose.

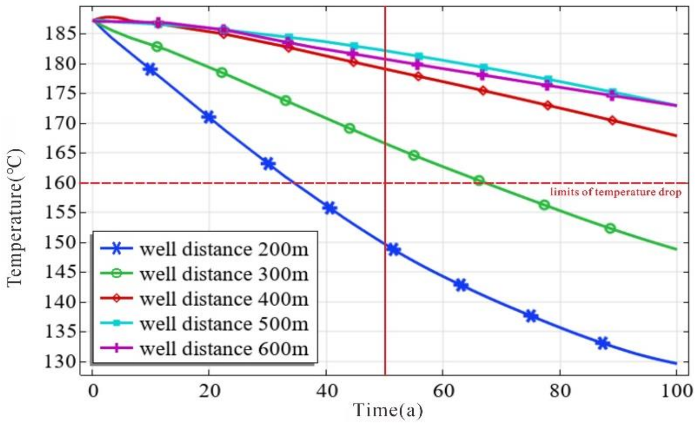

Figure 4: Temperature decline curve with different well distances with m_{inj}=100m^3/h.

When the permeability and thermal storage temperature are constant, the flow rate of the injected circulating well is different in the given same operation time, which will also lead to the difference of the heat extracted from the thermal storage under different schemes. In this study, the injection-production flow range is 100-160m^3/h. The figure 5 shows that the temperature drop curves of different flow schemes have different drop rates under the condition that the injection temperature is constant, the total flow of thermal storage cycle is constant, and the well spacing is constant. From the overall trend in the figure, under the same well spacing, the greater the flow, the faster the temperature drops, and the lower the temperature at the end of the mining operation; The smaller the flow, the longer the time of temperature reduction, and the higher the temperature at the end of mining operation. However, in combination with the mining utilization rate and the actual situation, the flow cannot be blindly reduced in order to pursue the mining life. It should be found that it is consistent with the mining life, and the flow is maximized to meet the economic value.

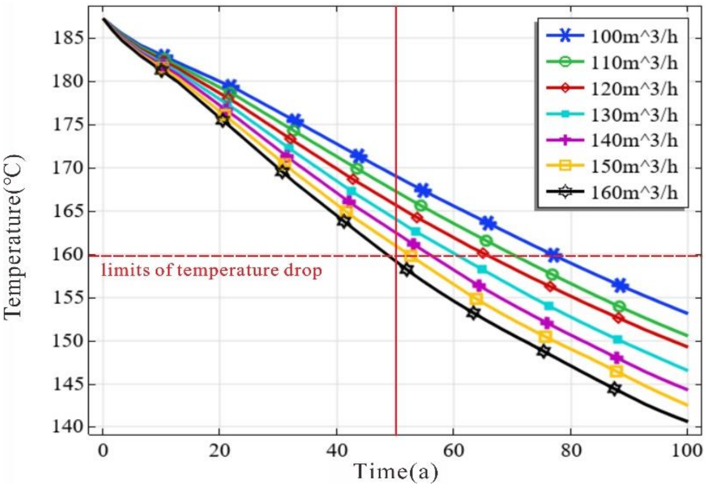

Figure 5: Temperature decline curve with different flow rates under *well dist*=350m.

At present, there is also a well layout development mode of 'Double Production-Injection' in the mining work. In this mode, due to the increase of injection water volume, the recoverable heat also increases in the same time, so the heat recovery efficiency is higher. Using this model and combining the influence of the above different mining factors on the hot-dry rock mining efficiency, the optimal hot-dry rock mining plan for the study area can be obtained, that is, within 50 years, the average temperature of 163 ℃ can be obtained by two production and two injection wells with well spacing of 400m and injection-production capacity of 110m^3/h. Under this scheme, the recoverable resources of the Bohai Bay Basin in 2000m×2000m range is 9.96 × 10^{14}J/a, equivalent to 3.40 standard coal × 10^4 tons.

4. CONCLUSION

Through establishing the conceptual model of hot-dry rock mining in the Bohai Bay Basin and simulating the change of mining efficiency due to different mining factors, the following conclusions and understanding are obtained. Some areas of the Bohai Bay Basin have a relatively high heat flow background and widely distributed metamorphic rock basement, which can be used as favorable areas for hot-dry rock mining. In the hot-dry rock mining system, the well spacing and water injection rate have an important impact on the hot-dry rock mining efficiency. The longer the well spacing is, the higher the temperature of the exploited well water is, the longer the mining life is, and the slower the temperature decreases; The higher the water injection flow, the lower the temperature of the production well water, and the faster the temperature decreases. According to the optimized exploitation schemes proposed in this study, the annual resource exploitation within 2km×2km is 9.96×10^{14}J equivalent to 3.40×10^{4} tons standard coal, the total amount of resources mined in 50 years is 4.98×10^{16}J, equivalent to 1.70×10^{6} tons standard coal. According to the thermal load index of 60-100W/m^2 per square meter of residential buildings (Xu, 2020), this exploitation scheme only needs 8000km^2 of hot-dry rock field area to meet the heating demand of Beijing residents, which is far less than the distribution range of deep hot-dry rock in Beijing. Therefore, the development and utilization of hot-dry rocks in the study area can achieve sustainable and clean heating in the area and make a contribution to the green and low-carbon cause.

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