China Geology 7 (2024) 409−421

China Geology

Journal homepage: http://chinageology.cgs.cn
https://www.sciencedirect.com/journal/china-geology

Two stages power generation test of the hot dry rock exploration and production demonstration project in the Gonghe Basin, northeastern Qinghai-Tibet plateau, China

Er-yong Zhang[a,*], Dong-guang Wen[a], Gui-ling Wang[b], Xian-peng Jin[a,*], Lin-you Zhang[a], Hai-dong Wu[a], Wen-shi Wang[c], Cheng-ming Ye[a], Wei Weng[d], Kuan Li[c], Jin-sheng Wu[e], Xian-chun Tang[f], Chong-yuan Zhang[g], Qing-da Feng[a], Sheng Lian[a], Li-sha Hu[a,*], Gui-lin Zhu[a], Xing-long Xie[a], Bin Wu[a], Dan Wang[a], Xue Niu[a], Zhao-xuan Niu[a], Dong-lin Liu[a], Hui Zhang[a], Wen-hao Xu[a], Shu-qing Yao[h], Li Yang[a]

[a] *Center for Hydrogeology and Environmental Geology Survey*, *China Geological Survey*, *Ministry of Natural Resources*, *Tianjin* 300304, *China*
[b] *Institute of Hydrogeology and Environmental Geology*, *Chinese Academy of Geological Sciences*, *China Geological Survey*, *Shijiazhuang* 050061, *China*
[c] *Institute of Exploration Techniques*, *Chinese Academy of Geological Sciences*, *China Geological Survey*, *Langfang* 065000, *China*
[d] *Institute of Exploration Engineering*, *China Geological Survey*, *Ministry of Natural Resources*, *Beijing* 100083, *China*
[e] *Institute of Exploration Technology*, *Chinese Academy of Geological Sciences*, *Chengdu* 611734, *China*
[f] *Chinese Academy of Geological Sciences*, *China Geological Survey*, *Beijing* 100037, *China*
[g] *Institute of Geomechanics*, *Chinese Academy of Geological Sciences*, *China Geological Survey*, *Beijing* 100081, *China*
[h] *Geoscience Documentation Center*, *China Geological Survey*, *Ministry of Natural Resources*, *Beijing* 100083, *China*

A R T I C L E I N F O

Article history:
Received 7 May 2024
Received in revised form 11 July 2024
Accepted 18 July 2024
Available online 19 July 2024

Keywords:
Power generation
Hot dry rock (HDR)
Enhanced geothermal system (EGS)
Genesis mechanism
Gonghe Basin
Directional drilling
Reservoir construction
Circulation test
Induced seismicity
Clean energy exploration engineering

A B S T R A C T

The Hot Dry Rock (HDR) is considered as a clean and renewable energy, poised to significantly contribute to the global energy decarbonization agenda. Many HDR projects worldwide have accumulated valuable experience in efficient drilling and completion, reservoir construction, and fracture simulation. In 2019, China Geological Survey (CGS) initiated a demonstration project of HDR exploration and production in the Gonghe Basin, aiming to overcome the setbacks faced by HDR projects. Over the ensuing four years, the Gonghe HDR project achieved the first power generation in 2021, followed by the second power generation test in 2022. After establishing the primary well group in the initial phase, two directional wells and one branch well were drilled. Noteworthy progress was made in successfully constructing the targeted reservoir, realizing inter-well connectivity, power generation and grid connection, implementing of the real-time micro-seismic monitoring. A closed-loop technical validation of the HDR exploration and production was completed. However, many technical challenges remain in the process of HDR industrialization, such as reservoir fracture network characterization, efficient drilling and completion, multiple fracturing treatment, continuous injection and production, as well as mitigation of induced seismicity and numerical simulation technology.

1. Introduction

Hot Dry Rock (HDR) is an abundant, clean, and renewable energy. Enhanced geothermal systems (EGS) is the primary technology for developing heat in HDR. More than 60 EGS projects have been initiated, including 13 projects for HDR power generation and 51 for coupling HDR and hydrothermal power generation. Currently, there are 5 operational EGS power generation projects, with a total installed capacity of approximately 12.2 MW (Pollack A et al., 2021).

The Fenton Hills project in the USA is the world's first HDR project. The project drilled four injection and production wells, utilizing hydraulic fracturing for reservoir construction. Subsequent sidetracking and hydraulic fracturing were employed to achieve effective interwell connectivity. The project was terminated in 1992 due to funding issues, with a cumulative power generation of 60 kW (Kelkar S et al.,

* Corresponding author: *E-mail address*: zeryong@mail.cgs.gov.cn (Er-yong Zhang); jinxp@mail.cgs.gov.cn (Xian-peng Jin); hulisha@mail.cgs.gov.cn (Li-sha Hu).

Literary editor: Xi-jie Chen
doi:10.31035/cg2024082
2096-5192/© 2024 China Geology Editorial Office.

2016). The Hijiori EGS project in Japan involved drilling four wells and conducting long-term circulation tests since 2000. A dual-cycle power generation capacity of 130 kW was achieved by the end of the tests. However, the tests were stopped due to the occurrence of thermal short-circuiting (Norio T et al., 1998; Kuriyagawa M et al., 1999). The Cooper Basin HDR project in Australia involved drilling four vertical wells with a depth of approximately 4500 m. Reservoir connectivity was achieved through hydraulic fracturing. The project achieved MW-scale power generation in 2013 (Baisch S et al., 2006; Ayling BF et al., 2016). The Pohang EGS project in Republic of Korea involved two wells over 4000 m in depth and used hydraulic fracturing for reservoir construction. However, the project was forced to stop after a 5.4-magnitude induced seismic occurred (Kim KH et al., 2018; Wassing BBT et al., 2021). These are all experimental or demonstration projects, accumulating valuable experiences in drilling and completion, reservoir construction, and simulation. However, these projects stopped due to issues such as funding, thermal short-circuiting, and induced seismicity, and have not yet achieved scaled-up or commercial development.

Nevertheless, many geological and engineering challenges remain in the HDR exploration and production. HDR is typically buried kilo meters beneath the Earth’s surface, characterized by hard and tight rocks, high temperatures, and high stresses (Tester JW et al., 2006; Xu TF et al., 2018). The engineering challenges for HDR exploration and production thus include high-temperature drilling and completion in hard rock, large-scale reservoir construction, efficient power conversion, and induced seismicity prediction and mitigation. Addressing these challenges is crucial for successfully exploring, developing, and utilizing HDR.

China Geological Survey (CGS) has just completed a demonstration project of HDR exploration and production in the Gonghe Basin, northeastern Qinghai–Tibet plateau, China. The stress types in the Gonghe Basin are diverse. From 1500 to 3477 m depth, the stress is characterized by strike-slip type, while beyond 3477 m depth, it transitions to thrust stress type. The difference between the minimum horizontal stress (Sh_{min}) and vertical stress (S_v) is minimal, whereas there is a significant difference between Sh_{min}, S_v, and the maximum horizontal stress (Sh_{max}), reaching up to 20–30 MPa. The reservoir rock formations in the basin exhibit complex natural fracture systems, a phenomenon that is uncommon even in existing EGS projects worldwide. Furthermore, the region where the HDR formations are located in the Gonghe Basin has a relatively high population density, presenting greater challenges for the prediction and mitigation of seismic activity in the development of HDR resources.

From 2019 to 2021, the project drilled three wells and achieved its first power generation (Zhang EY et al., 2022; Wen DG et al., 2023). Subsequently, the project drilled two additional wells and one branch well, followed by conducting interwell connectivity and flow tests to enhance the geothermal reservoir. The Qinghai Gonghe HDR project has achieved large-scale reservoir development and multi-well cyclic injection and production of HDR under conditions of high *in-situ* stress and complex fracture networks. Power generation and grid connection have been successfully performed, and induced seismic activity was controlled within the red-light threshold of the Traffic Light system.

This article systematically summarizes the research progress of the Gonghe HDR project, including geological exploration and evaluation, geophysical survey, drilling, reservoir construction, power generation, seismic risk evaluation, and numerical simulation. The aim is to provide a reference for the development of HDR under similar geological conditions, offering a technical roadmap and engineering experience, and serving as a new approach and model for the development and utilization of renewable clean energy in China.

2. Geological and geothermal background

2.1. Regional geological conditions

The Gonghe Basin is situated on the northeastern margin of the Qinghai-Tibetan Plateau, with geographical coordinates from 98°46′ to 101°22′ East and 35°27′ to 36°56′ North. The basin can be divided into the Chaka sub-basin, the Gonghe sub-basin, and the Guide sub-basin. Most faults occur along the edges of uplift zones and are high-angle compress-torsional (Jia L et al., 2017).

The basement is primarily composed of Pre-Triassic metamorphic rocks and Indosinian-Yanshanian granite bodies. The above sedimentary cover from bottom to top consists of the fluvial-lacustrine sediments. The maximum burial depth of the basement exceeds 5000 m (Fig. 1). The burial depth of the basement becomes shallow gradually from west to east until the Waliguan Mountain is exposed at the surface (Qiang M et al., 2016; Gao J et al., 2020). Due to the existence of the dextral strike-slip and thrust Xinjie-Waliguan Mountain Fault, the basement is exposed in large areas in the eastern margin of the basin (Zhu YQ et al., 2022; Zhang EY et al., 2022).

2.2. Regional geothermal conditions

The Gonghe Basin has a significant regional thermal anomaly within the northeast margin of the Qinghai-Tibetan Plateau (Jiang G et al., 2019). According to the drilling results, the current geothermal field shows extreme inhomogeneity. The temperature of well Gongcan 1 in the western part of the basin does not exceed 170°C at a depth of 5026 m, with the heat flow about 55 mW/m^2. However, the temperature generally reaches 180°C at a depth range of 3200–3300 m, with the average earth heat flow about 102 mW/m^2 in the eastern part of the basin (Zhang C et al., 2021). The existing drilling in the Guide sub-basin shows a relatively higher shallow geo-temperature gradient, which is affected by thermal convection. As the depth increases, the deep geothermal gradient decreases. The average heat flow in the Guide sub-basin is about 75 MW/m^2 (Zhang C et al., 2020;

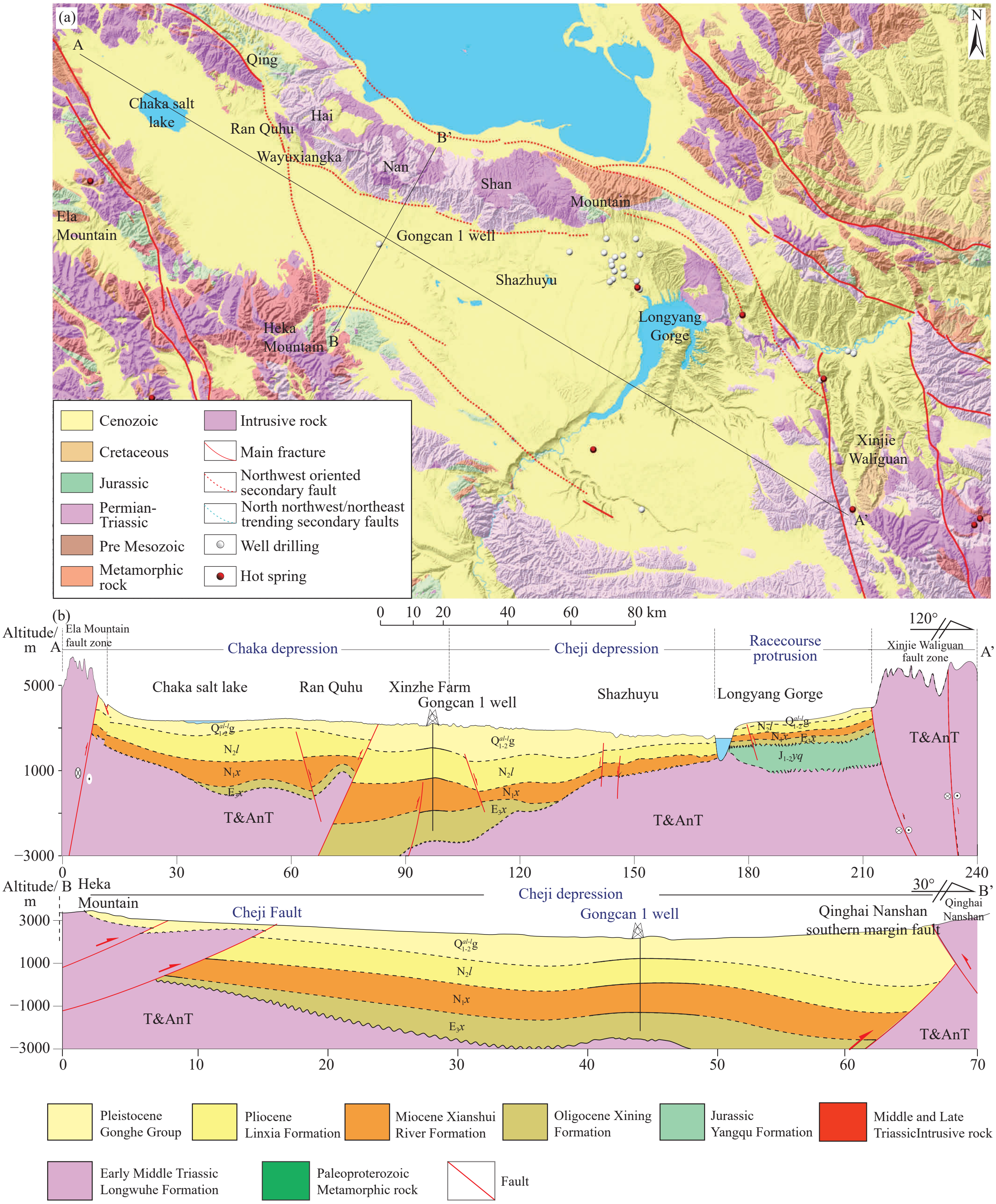


Fig. 1. Geological map of the Gonghe Basin. a–geological map; b–schematic diagram of geological structure cross-section.

Lu R et al., 2024; Feng YF et al., 2018).

2.3. HDR genesis mechanism in the Gonghe Basin

Based on Geothermal geological, geophysical, and numerical simulation work, the heat source within the Gonghe Basin can be mainly divided into three aspects (Fig. 2). Firstly, crustal thickening leads to a concurrent increase in the thickness of radioactive rock bodies within the crust, elevating the regional radiogenic heat production level due to

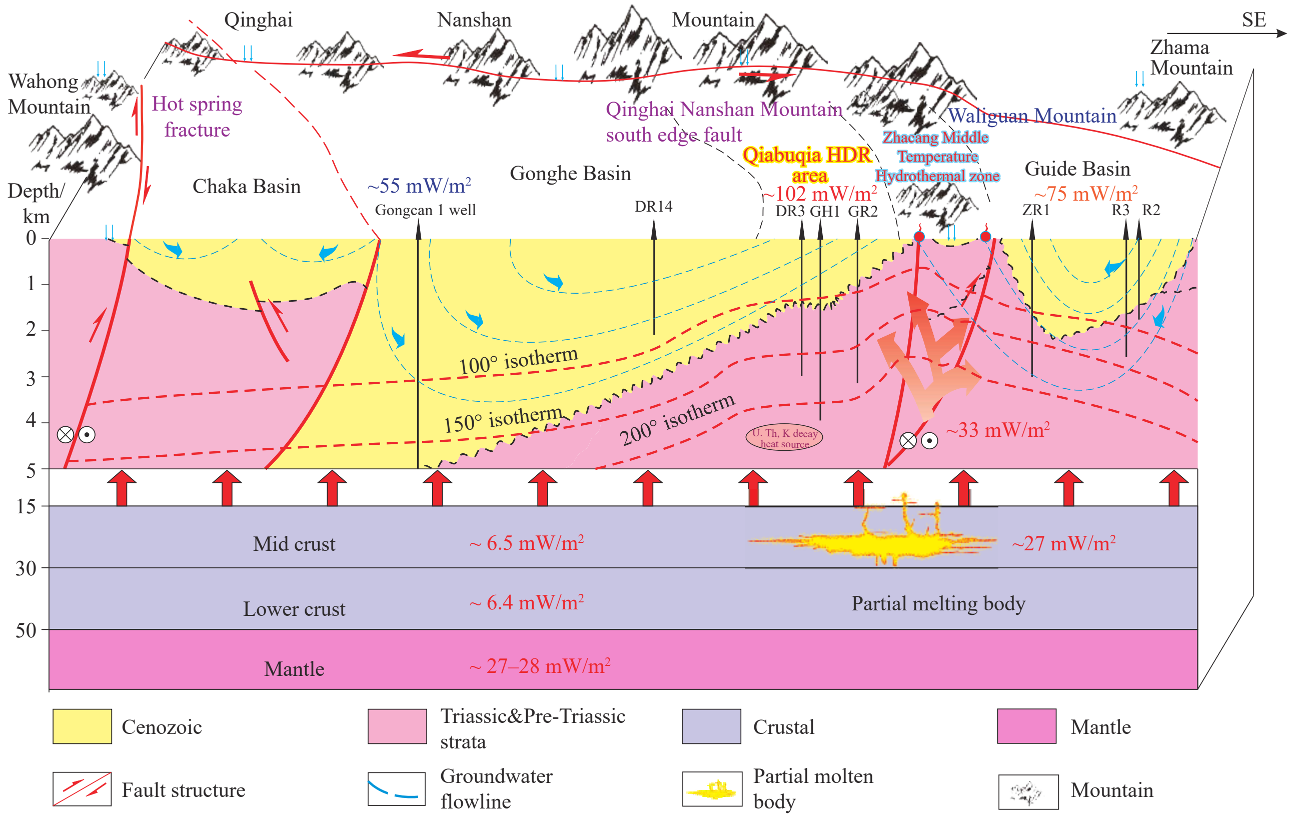


Fig. 2. Schematic diagram of the HDR genesis mechanism in the Gonghe Basin.

volumetric effects. Secondly, the Gonghe Basin is situated in a crustal-mantle uplift area, where thermal dome activity results in the accumulation of significant heat within the basin. Thirdly, the continuous dynamic shear friction heat generation from the multi-level, nearly horizontally distributed ductile detachment and detachment nappe structural interfaces beneath the basin. It induces the formation of abnormal heat sources in local partial melting layers within the crust. The HDR in the Gonghe Basin has regional distribution characteristics. Considering the geothermal geological characteristics of the HDR, it is speculated that the dominant HDR target area is in the Qiabuqia-Dalianhai area.

3. Progress of the Gonghe HDR project

The HDR exploration and production demonstration project in the Gonghe Basin was officially launched in 2019. The project can be divided into two stages: The first stage lasts from 2019 to 2021, and the second stage starts from 2022. In the first stage, three wells over 4000 m were drilled. The large-scale reservoir construction was successfully carried out in 2020, followed by the conduction of interwell connectivity tests and experimental power generation from HDR in 2021. Interwell connectivity and flow tests were taken to improve the reservoir and enhance injection and production efficiency. Subsequently, the second power generation test was successfully carried out in 2022. Two directional wells over 4000 m in depth and one branch well were drilled in this stage. Power generation tests were conducted on a 340 kW unit and a 1.2 MW unit, respectively. In summary, from 2019 to 2022, five directional wells over 4000 m deep and one branch well were drilled, two power generation tests were carried out, and many significant experimental param were achieved.

3.1. Geothermal geological characteristics of the production test site

The lithology of the sedimentary covers in the production test site is mainly composed of Neogene and Quaternary fluvio-lacustrine mudstone and muddy siltstone deposition with fine particle size, poor permeability, and low thermal conductivity (about 1.59 W/m·K), which is the ideal thermal insulation layer for HDR formation. The basement under the sedimentary covers is composed of Mesozoic granitoids with an age of about 242 Ma in the production test site. The granitoids are of low porosity and high thermal conductivity (about 2.51 W/m·K). The granitoid mass develops two main sequences, bounded by 2950 m. The upper part is mainly composed of syenogranite and monzogranite, and the lower part is primarily granodiorite. The granitoids are mainly coarse- to medium- grained, with a porphyritic texture. The content of brittle minerals could reach more than 80%.

According to the drilling result, the thickness of sedimentary covers reaches 1360 m. The average temperature gradient is about 64.2°C/km within sedimentary covers and is about 40.5°C/km within granitic basement. The temperature reached 209°C at the bottom of well GH-01, which makes it a maximum temperature at the same depth never found in

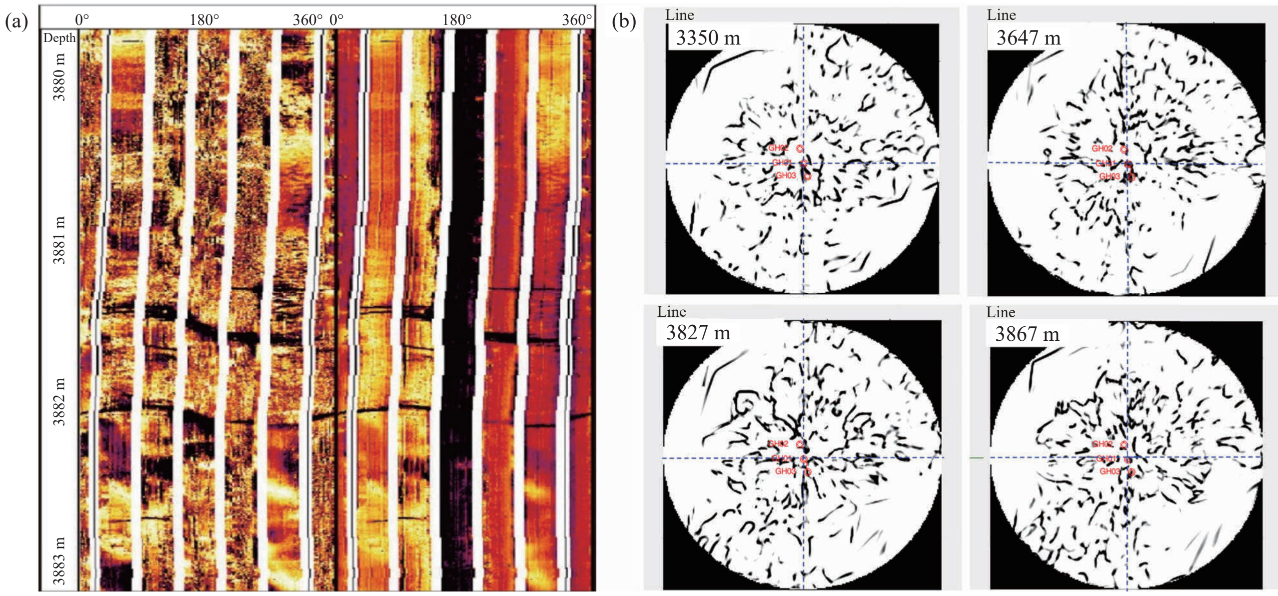


Fig. 3. Micro scanner image and VSP image of the HDR reservoir section in well GH-01. a–Micro scanner image; b–VSP image.

continental China (Zhang EY et al., 2022).

The HDR exploration and production demonstration project in the Gonghe Basin proved that the shear action of natural fractures constitutes the main mechanism of reservoir development, which is of great value for reservoir construction. The characteristics of the natural fracture within the reservoir were evaluated through the three-dimensional seismic, logging, and VSP geophysical analysis. The data indicate that the northwest and northeast directions are the two major orientations of natural fracture, in which the northwest is mainly thrust and shear fracture, and the northeast is mainly tension fracture. The joint detection results show that the natural fracture occurred at a steeply inclined angle, and the angle can reach about 70°. The density of the natural fracture in different depths varies greatly. The natural fracture density in the shallow is much higher than that in the deep reservoir. The natural fractures in the intervals of 3636–3740 m, 3816–3883 m, and 3930–3982 m are relatively developed (Fig. 3). From the bottom of well GH-01 to well GH-02 and the northwest side of well GH-01, natural fractures are densely developed. The main water-filling areas are distributed in the middle and southwest of the working area.

3.2. Drilling and completion of the wells

From 2019 to 2021, one vertical well (GH-01) and two directional wells (GH-02 and GH-03) were drilled to a depth of 4000 m, with a bottom hole temperature of approximately 209°C. During this period, routine logging, imaging logging, coring, and testing fracturing were conducted in these wells. Additionally, large-scale fracturing operations were carried out.

In 2022, two direction wells, GH-04 and GH-05, were drilled for reservoir enhancement. Additionally, a branch well, GH-03A, was drilled. From 2019 to 2022, the completion cycle of HDR drilling continued to decrease, with a maximum reduction of 35%.

All five wells were designed with a three-section casing program. Specifically, GH-04, GH-05, and GH-03A targeted specific points in the upper and lower depth, referred to as the first and second targets, respectively. The goal was to make the drilling trajectory intersect as many opening fractures as possible within the geothermal reservoirs. As a result, the five wells composed a well system for HDR injection and production, achieving connectivity among them.

During drilling, various down-hole tools, including air hammer, percussive hydraulic shock absorbers, wear-resistant rotary drilling tools, high-temperature turbine drilling tools, and high-energy hydraulic hammer were extensively tested. These tests led to developing a composite drilling technology for geothermal development. This innovative approach combined high-speed and strong-reaming tri-cone bits with high-temperature down-hole motors, high-temperature measurement while drilling (MWD), and a drilling fluid cooling system. The result was a rate of penetration (ROP) exceeding 1-fold of conventional rotary drilling, with an average ROP of 4.6 m per hour.

This advancement represents a significant milestone in geothermal energy drilling and underscores the ongoing efforts to harness sustainable energy from HDR formations.

For directional drilling, a bottom-hole power composite-controlled drilling technology and a specially developed ultra-high temperature and high-pressure inclinometer (maximum pressure of 100 MPa and temperature of 230°C for four hours) were employed. This combination achieved high-precision targeting of directional wells in high-temperature hard rocks, with a target radius ranging from 1.5 m to 9.8 m.

Additionally, high-temperature turbo-drill tool, paired with polycrystalline diamond compact (PDC) bits, facilitated high-speed drilling in granite formations, maintaining high rates of penetration (ROP). Jet-assisted hydraulic hammers and hydraulic shock absorbers enhanced rock-breaking efficiency under low-frequency, high-impact stress conditions. Furthermore, the energy storage hydraulic shock-absorbing rotary drilling tools significantly increased drilling speed in hard and brittle formations, achieving a drilling efficiency of more than three times that of conventional rotary drilling.

A high-temperature water-based, environmentally friendly drilling fluid system capable of withstanding temperatures up to 240°C was also developed. This system met requirements for cuttings transportation, borehole stability, and lubrication in high-temperature geothermal environments. Coupled with a drilling fluid cooling system, it reduced circulating temperature by 25°C, ensuring optimal working conditions and extended service life for down-hole measurement instruments.

Regarding completion techniques, silica powder was added to enhance the high-temperature resistance of cement stone. High porosity sieve tubes were used in the geothermal reservoir section to facilitate overall stage fracturing. Additionally, high-temperature casings were employed during well completion to ensure well integrity throughout subsequent reservoir construction and heat extraction processes.

Lastly, in the realm of geothermal side drilling technology, constructing branch wells in cased boreholes within HDR formations remains challenging due to limited experience. Despite these difficulties, branch well GH-03A was successfully drilled at a depth of 3058 m with directional footage of 649 m. By overcoming the complexities of opening casing windows and simultaneous side drilling in high-temperature hard rocks, a technical system for small borehole directional drilling in high-temperature environments was established. To protect HDR reservoirs and prevent drilling fluid or completion fluid from blocking fractures, calcium carbonate was used as a weighting agent and a dual-density cement slurry system was employed for cementing during completion.

3.3. Reservoir construction

The success of the reservoir construction in HDR will directly affect the heat production efficiency and the overall injection and production performance. A favorite geothermal reservoir has a large heat exchange area and low impedance, allowing adequate flow of circulating fluid and effectively exchanging heat with the fluid. However, the construction of an HDR reservoir system is challenging due to the diverse geological types and the complex stress conditions inherent to HDR reservoirs. This difficulty is further compounded by the limited number of successful HDR fracturing development activities. To ensure the safe and efficient construction of granite formations under the complex geological conditions of strong compression, pressure torsion and high stress in the Gonghe Basin, the reservoir construction process in HDR is divided into three stages: test fracturing, pilot reservoir construction, and large-scale reservoir stimulating (Zhang EY et al., 2022). This article mainly analyzed the results and param achieved by the operation of reservoir construction.

The test fracturing included diagnostic fracture injection test (DFIT), acid test, step increase-decrease injection rate test, continuous intermittent injection test, temporary plugging agent test, glue test, etc. The test fracturing obtained an effective modified reservoir volume of 600000 m^3 and an *in-situ* permeability of 0.026 mD in the test reservoir. DFIT can obtain data such as rupture gradient, closure pressure, formation pressure, and effective permeability, which can be used to understand the formation condition and provide a basis for adjusting the main fracturing param. After the DFIT was completed, the shut-in pressure was 23.7 MPa, and the pressure drop data were continuously monitored for a long time, which were analyzed and interpreted using the G-function analysis method. The curve characteristics show that the natural fractures are developed in the formation, the expansion of main fracture is not obvious (Fig. 4). After the natural fracture closed, the distant fractures in the reservoir continued to extend.

Pilot reservoir construction severs primarily to make technical preparations for large-scale construction. The HDR shear fracturing process tests under different injection rates and fluid volumes were conducted by analyzing the extension characteristics of reservoir fractures under a certain scale of fluid volume. The most important purpose was to determine the corresponding relationship between pressure, injection rate, and micro-seismic energy levels during fracturing and pump-stop pressure drop. As is shown in Fig. 5, higher magnitude events (> M_L 1.5) generally occurred during pump-stop pressure drop rather than during fracturing, indicating that the ongoing fracture closure process is more likely to cause the release of formation energy. Furthermore, while low injection rates do not reduce the induced seismic level, they may not contribute to the safety of fracture expansion. Determine the upper limits of injection rate and pressure under the allowable influence of the maximum vibration of the site, to optimize the reasonable injection rate adopted in the case of long-term shear fracturing fracture expansion.

Large-scale reservoir construction was divided into 6 units. The pumping procedure of each unit was flexibly adjusted according to the monitoring results of construction and fracture expansion. HDR reservoir construction generally generated shearing fractures, promoting fracture expansion, increasing construction volume. Research was conducted in terms of technology and materials, forming the key HDR fracturing technology such as staged fracturing, maintaining a low injection rate, employing longer cycles, injecting multi fluids, gradually reduce the flow rate until the pumping stops and so on. A controlled injection strategy with low injection rate of 0–3 m^3/min and sustained pumping duration of 8–24 hours was implemented to achieve effective rock shear and fracture expansion under low micro-seismic energy level. Continuous pumping measures were used to reduce the effects of pore pressure fluctuations, and stepless variable speed fracturing equipment was used to gradually reduce the flow rate until the pumping stops. Through the shock absorption technical methods and fracture expansion process

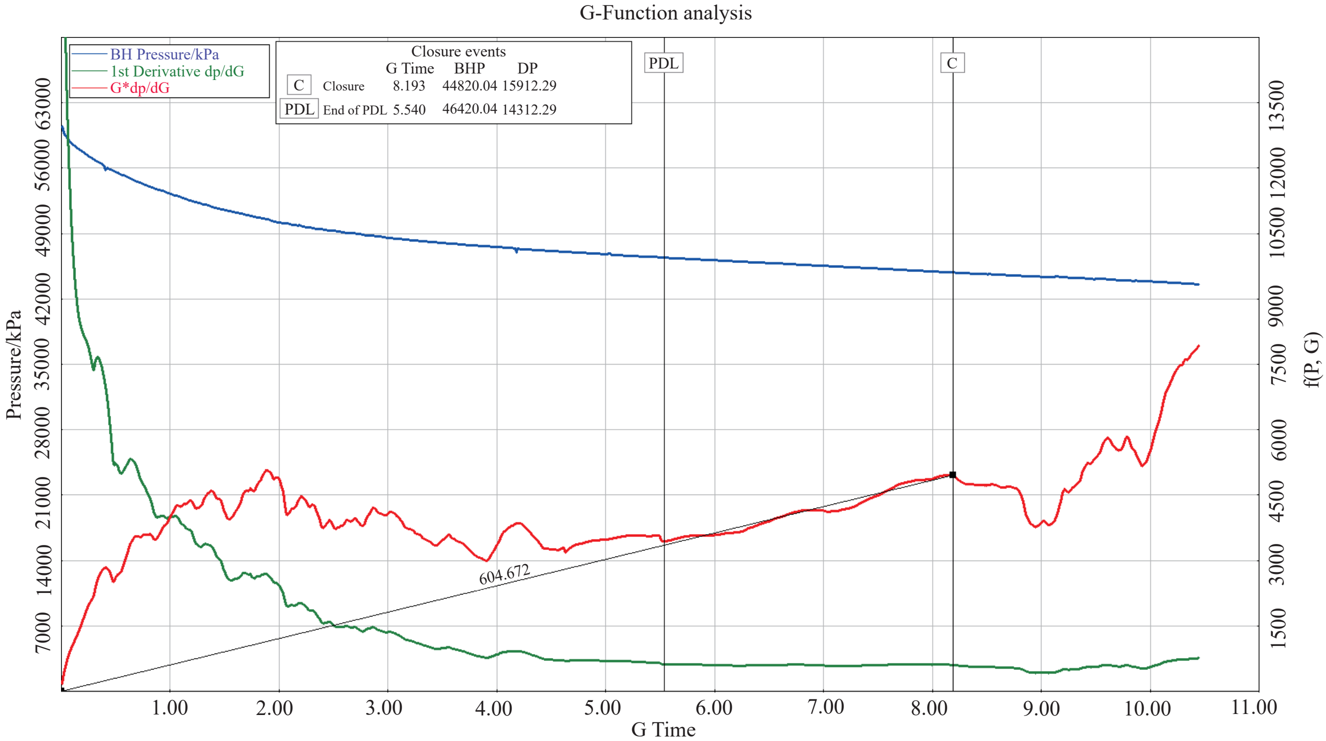


Fig. 4. G-functional curves during diagnostic fracturing injection test (DFIT).

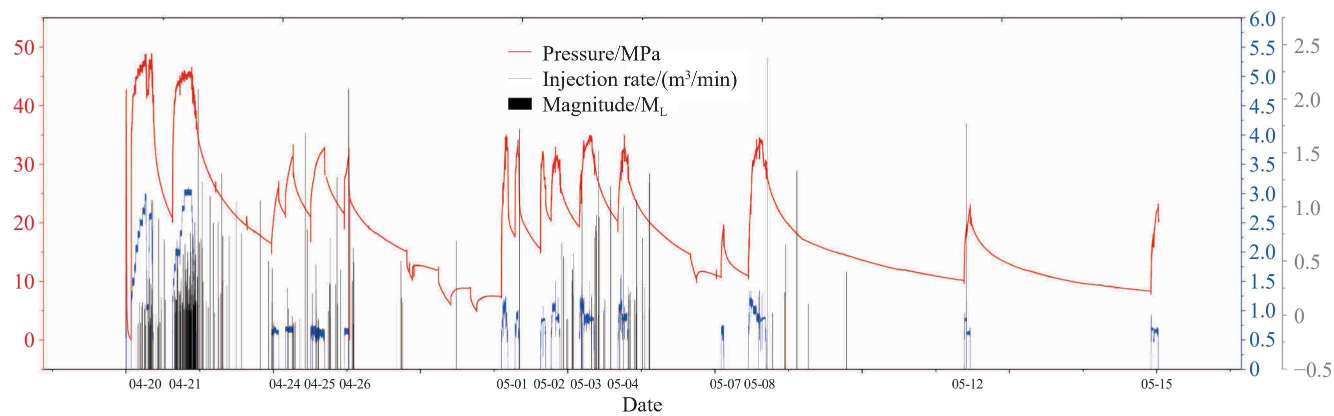


Fig. 5. Injection rate, pressure, and magnitude records during reservoir construction.

optimization, the large-scale reservoir construction was gradually completed in phases and units.

Considering safety factors, the fluid volume of the unit was increased as far as possible, and the fluid and temporary plugging process was optimized and adjusted to achieve a larger modified volume and a more uniform effect of modification. The cumulative fluid volume used in this stage exceeded 20000 m^3, the maximum injection rate was 3.05 m^3/min, the maximum pressure was 48.1 MPa (Fig.6), the effective modified reservoir volume was more than 30000000 m^3, with the hydraulic fracture system in a clear advantage direction and uniform distribution.

3.4. Interwell connectivity and flow test

3.4.1. Numerical simulation and analysis

The development of HDR consists of two key phases: Reservoir construction and subsequent power generation. The critical issue in both phases is the spatial and temporal evolution of stress, hydrodynamic, temperature and chemical fields, and more generally, thermal-hydrodynamic-mechanical-chemical (THMC) coupling. A large number of numerical simulation studies have been conducted worldwide for the investigation and development experiments in HDR development (Bruno MS et al., 2012; Ghassemi A et al., 2015; Jeanne P et al., 2015; Kalinina EA et al., 2012). At present, most studies do not consider the effects of chemical fields, lack a systematic analysis of how mechanics and chemistry affect fractures and fluids, and few simulation studies have investigated the effects of fully coupled THMC interactions on the evolution of geothermal reservoirs. On this basis, this project carried out the THMC multi-field coupled simulation and guided HDR injection and production according to the simulation results. Specifically, it includes:

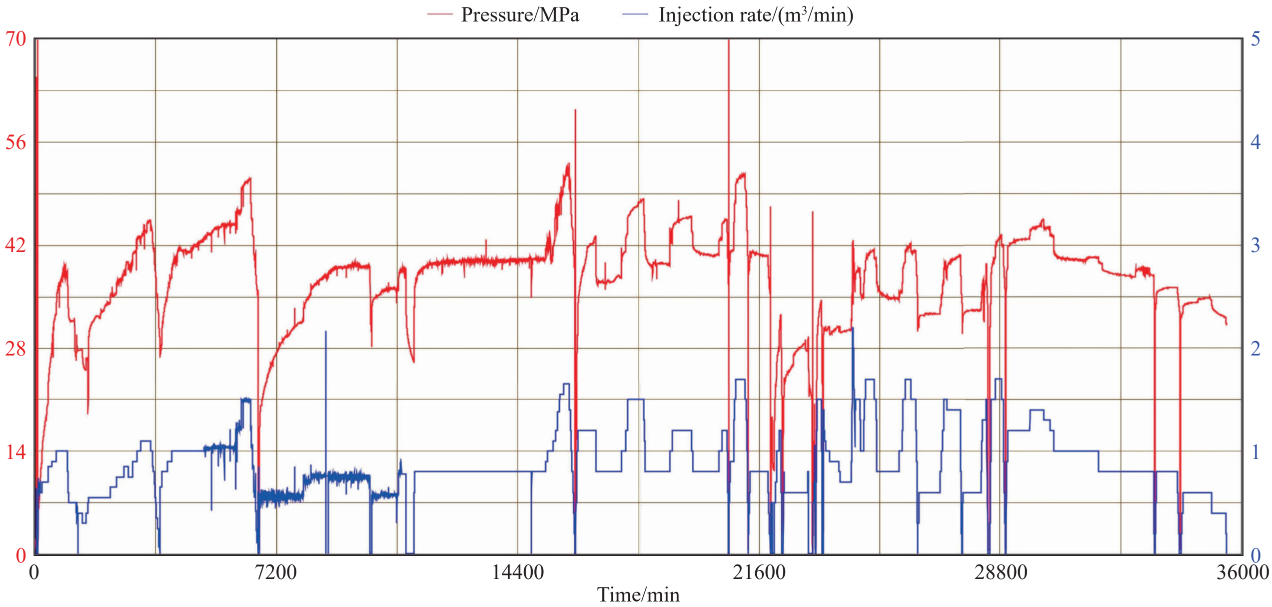


Fig. 6. Pressure and injection rate records of well GH-01 well during large-scale reservoir stimulating.

(1) Establishing a three-dimensional geological model of the development site including formation structure and fracture network; (2) conducting coupled THMC numerical simulations to adjust and optimize the engineering param for reservoir construction and power generation; (3) simulating the evolution trend of THMC field, predicting the change of production capacity over time, and proposing development recommendation.

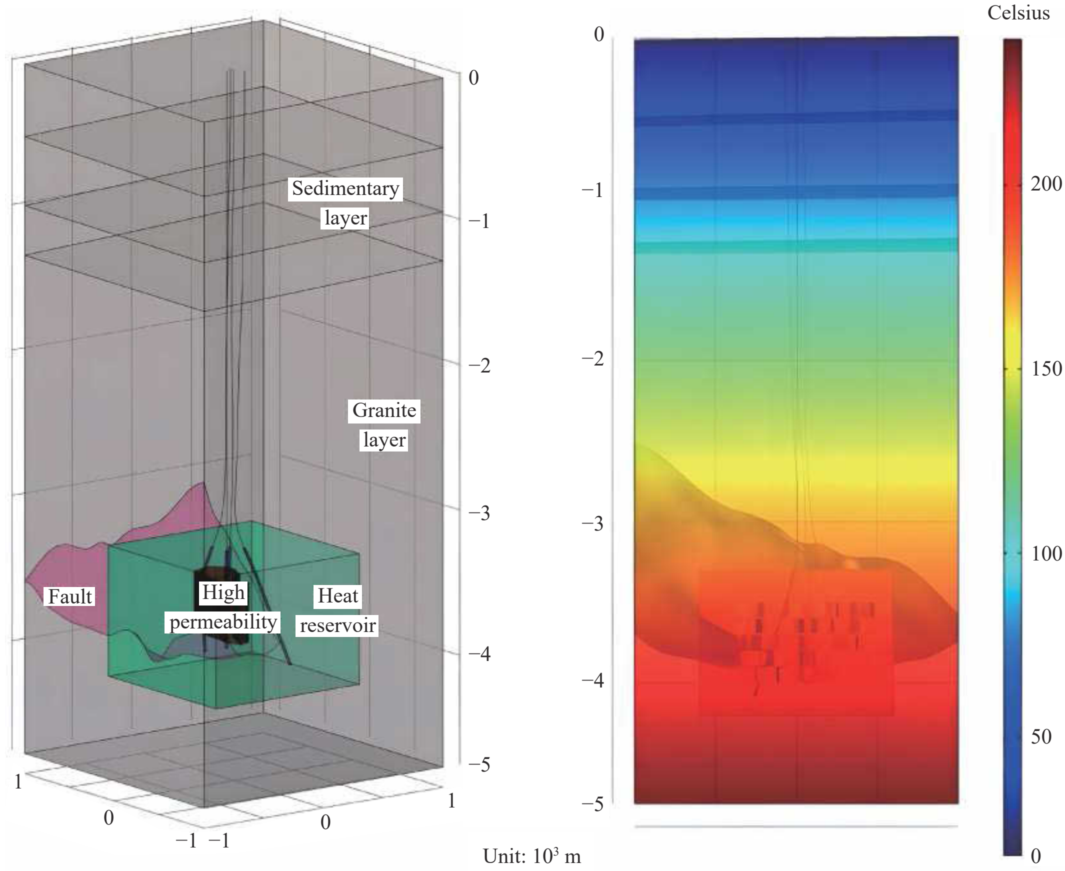
Darcy's law and fracture flow were used to simulate the fluid field of the fracture systems and the ordinary strata; heat transfer in porous medium and fractures were used to simulate the solid and fluid heat conduction of the fracture systems and sedimentary layer; and non-isothermal pipeline flow was used to simulate the heat loss in the production wells. Meanwhile, a frontal dynamic fracture simulation study was carried out to realize the variation of fracture opening with stress and thermal conductivity with fracture opening, improving multi-field simulation's reliability. The model param were corrected according to the field injection and production tests, and the simulation results show that the temperature and flow rate fit well with the observation results.

The simulated depth range is 0–5000 m, and the model size is 2000×2000×5000 m. The 0–1360 m depth is sediment layers, and 1360–5000 m is granite. There are faults distributed near the thermal reservoir (Fig. 7). According to the 3D network fracture model inverted by micro-seismic monitoring data, a fully coupled iterative 3D numerical model of flow, heat transfer, and fracture changes in the reservoir was constructed. According to the fracture distribution, the depth of the thermal reservoir is 3300–4300 m, with a total volume of 1.44×10^6 m^3. The initial temperature is assigned based on the observed geothermal gradient. Wells were modeled based on the actual trajectory of each well (Fig. 8).

Different injection and production schemes for the five wells were simulated to determine the best one. According to the injection and production experiments after the implementation of the wells GH-03A, GH-04, and GH-05, the maximum pressure of well GH-01 is 40 MPa, the temperature is about 130°C, and the flow rate is about 120 m^3 per hour. The model param were adjusted according to the results of the injection and production experiments, and the simulation results were further corrected. The simulation scenarios contain single injection and multiple extractions, multiple injections and single extraction, multiple injections and two extractions, and so on.

The results show that the multiple injections and single extraction (well GH-01) or the multiple injections and two extractions (wells GH-01 and GH-02) scheme has the best effect, with a maximum power generation of multiple injections and single extraction reaching 0.08 MW, and that of multiple injections and two extractions reaching 0.13 MW. Due to the low injection rate of wells GH-02 and GH-05, the extraction flow rate of well GH-01 is 57.4 m^3 /h and the recovery temperature is 120.4°C, indicating a little impact. The typical distribution of the reservoir fracture flow heat exchange simulation is shown in Fig. 9.

The effects of different well spacing, injection rates, injection temperatures, and well types were also simulated and compared. The results show that the pressure increased at the same injection rate as the well space increased, while the maximum power generation did not change significantly. However, the longer the duration, the higher the total recoverable heat. As the injection pressure increased, the maximum power generation increased, but the duration and the total recoverable heat decreased. Horizontal wells generated far more electricity than the vertical well group model. Power generation also lasted longer, but the construction of the horizontal wells is difficult and costly. With the future development of drilling technology, the development of horizontal wells should be considered. Recovery speed is faster under high-temperature injection



(a) Schematic diagram of geological modeling (b) Initial temperature condition

Fig. 7. Schematic diagram of geological modeling and initial temperature condition. a–geological modeling; b–initial temperature condition.

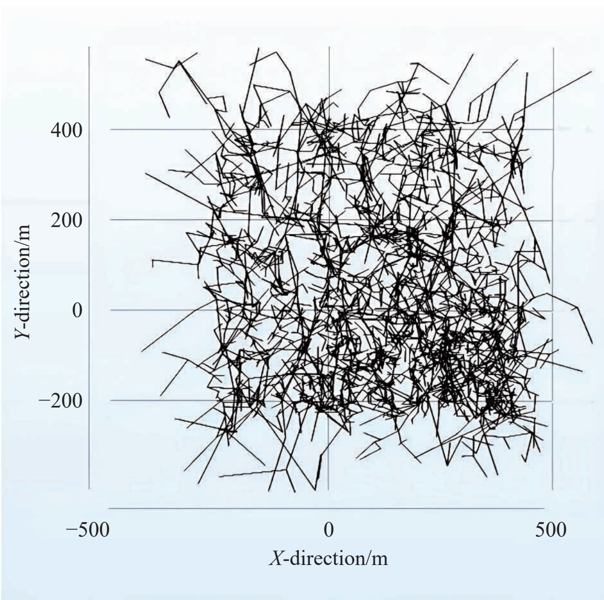


Fig. 8. Distribution of reservoir fracture network.

conditions, but higher injection temperatures mean more wasted energy. Simply increasing the injection temperature is not recommended.

Numerical simulations were also conducted such as hydraulic fracturing and reservoir construction, water and rock interaction reaction, thermal reservoir stability, stress and dynamic fracture, deep heat source thermal evolution, and so on. These studies provided data support for parameter distribution, parameter acquisition, reservoir stability, fracture spread, heat source mechanism, etc.

3.4.2. On-site test

The artificial fracture system formed by the reservoir construction needs to be effectively connected between the injection and production wells to form a sufficient heat exchange area. Therefore, it is necessary to maximize the size of the connectivity fractures and reduce the circulation impedance during the interwell communication and flow tests, in order to effectively use the full potential of reservoir modification and expand the scale of injection and production.

To test the connectivity between multiple wells, a designed well injection was used to observe the pressure and flow rate of the production wells at the beginning of the 2021 interwell circulation test to obtain the connectivity of different circuits efficiently. The test results reflected that the connectivity between well GH-02 and well GH-01 was better than that of well GH-03, so targeted construction measures were taken for the circuit between well GH-01 and well GH-03. In order to overcome the problems in the artificial geothermal reservoir, the technicians adopted the stimulation scheme of alternating injection and deep perforation based on a fine interpretation of fractures, which effectively enhanced the connectivity between wells (Zhang EY et al., 2022). In

2022, similar stimulation was carried out for the injection and production circuit of wells GH-01, GH-04, and GH-05 with obvious effects, creating favorable conditions for long-term cycle tests.

The reservoir stress is under strong compression and torsion, causing difficulties in the injection and production. To reduce the pressure and expand the scale of injection and production, multi-stage acidizing measures were mainly adopted in the long-term cycle test stage, and the effect of chemical stimulation was strengthened with the circuit to achieve the construction purpose. In 2021, the circulation flow rate reached 15–22 m^3/h, with the temperature over 125°C. In 2022, with the additiont of two new wells and one branch well, the technicians focused on optimizing the well group setup, controlling injection and production param, and forming a stable cycle mode of five well groups. The instantaneous maximum production volume of the well group was 70 m^3/h with an average flow rate of 24–32m^3/h, and the maximum temperature was 124.3°C.

3.5. Evaluation of the reservoir volume

3.5.1. Micro-seismic monitoring results

Artificially constructed HDR reservoirs are commonly evaluated through micro-seismic monitoring (Gan HN et al., 2020; Warpinski NR et al., 2009). It enables us to infer the reservoir's scale, shape, hydraulic fracturing network structure, and *in-situ* stress characteristics, which are very important param for making the HDR development plans. It is imperative to establish a micro-seismic monitoring system tailored to the lithological and stratigraphic features of the Gonghe HDR project site (Cladouhos TT et al., 2016).

The monitoring system centered around well GH-01, with 12 measurement lines spaced 25 m apart and comprising 1516 monitoring channels. Additionally, a matrix-shaped array of 60 shallow well monitoring stations within a 5 km radius of GH-01, equipped with high-precision three-component detectors at depths of 15–20 m, was deployed. Ground monitoring data were transmitted via wired cable, while

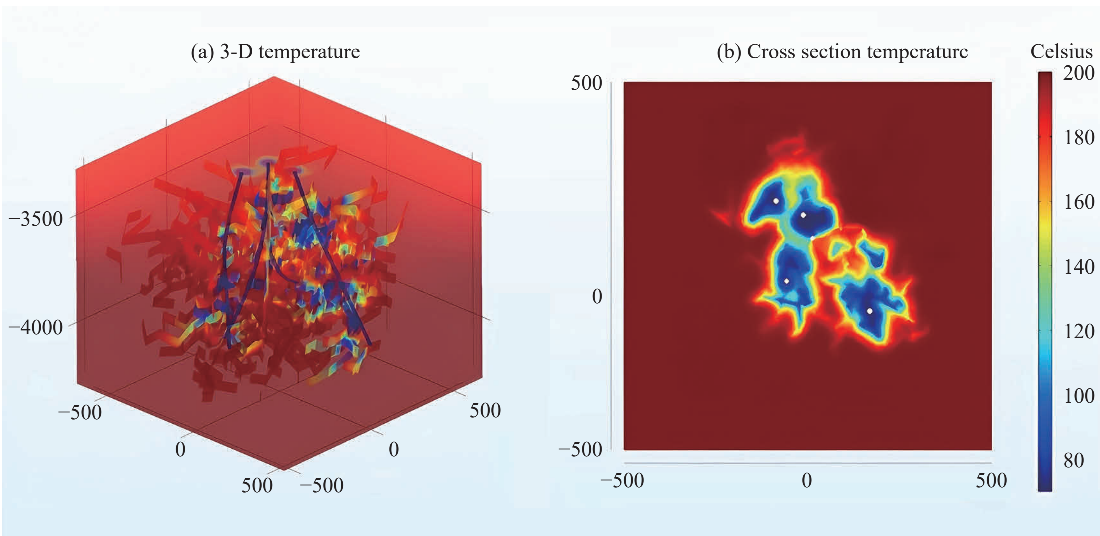


Fig. 9. Typical distribution of reservoir fracture flow heat exchange simulation (2000 days; a–3D temperature; b–Cross section temperature).

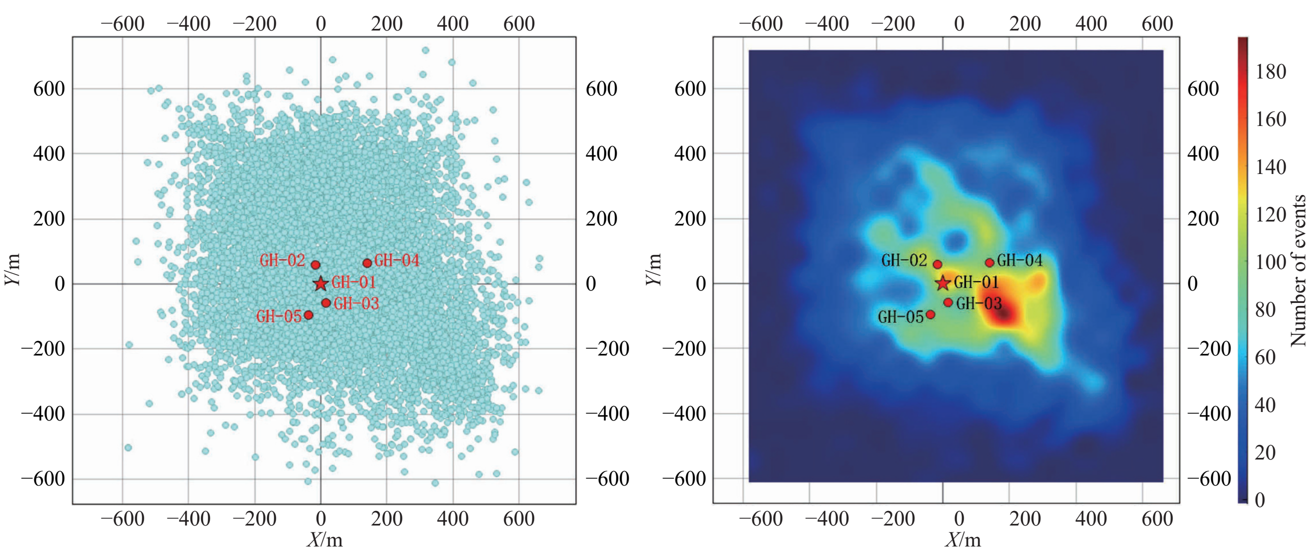


Fig. 10. Spatial distribution pattern of micro-seismic events (left) and micro-seismic number of events (right).

shallow well monitoring data utilized a local area wireless network, facilitating real-time transmission to the data processing center. The spatial distribution pattern of micro-seismic events and micro-seismic number of events is shown in Fig. 10.

Micro-seismic monitoring data collected from the site were pre-processed, including static and dynamic corrections, noise suppression, and micro-seismic event positioning through weak signal extraction, polarity processing, and focal scanning. Multi-wave seismic wave field techniques were employed to extract micro-seismic signals in high noise backgrounds effectively. Subsequent interpretations involved source mechanism inversion, ground stress inversion, fracture network modeling, hydraulic fracture permeability inversion, and Stimulated Reservoir Volume (SRV) calculation, using a fracture network model-based SRV calculation method to estimate HDR reservoir fracture network volume accurately.

The monitoring results indicate that the orientation of the stress field of the reservoir predominantly aligns with the maximum horizontal principal stress towards the north and east. Artificial hydraulic fractures exhibit orientations extending both north-east and north-west directions, varying across different fracturing stages. The inclination angle of artificial hydraulic fractures ranges from 40° to 85°, with early fracturing primarily targeting high-angle fractures. Micro-seismic events predominantly correspond to strik-slip mechanisms, indicating shear rupture with smaller hydraulic fractures tend to have higher shear components. Over the period from 2019 to 2022, the total volume of reservoir modification is estimated at approximately 9×10^7 m^3.

3.5.2. Electromagnetic monitoring results

Hydraulic fracturing induced the displacement of high-resistivity reservoir fractures with low-resistivity fracturing fluid, thus altering the reservoir’s electrical structure, forming the basis for fracturing monitoring using the time-frequency electromagnetic method. Additionally, Wang ZG et al. (2016) demonstrated that in areas characterized by small terrain relief, minimal interference, and simple geological structures, anomalies such as relative amplitude fluctuations and high resistivity deviations tend to occur during hydraulic fracturing processes, particularly in shallow horizontal wells. These anomalies, observed in conjunction with the perforation points and depths of the horizontal wells, underscored the feasibility of employing the time-frequency electromagnetic method for hydraulic fracturing monitoring.

A time-frequency electromagnetic method ground surface monitoring network was established at the HDR site, covering an area of 0.765 km^2. Monitoring during this period revealed the primary direction of fracturing fluid propagation to be north-northwest. Moreover, the abundance of fluid at well GH-01 was observed to be greater in the northeast compared to the southwest. Fluid pathways between well GH-01 and well GH-03 were identified, with fluid dispersion extending southeastward from the bottom of well GH-03. Estimated characteristics of the reservoir within the HDR site depicted an irregular body, approximately 600 m in northeast-southwest length and 360 m in northwest-southeast width, with a maximum thickness of about 350 m and an average thickness of around 150 m. The longitudinal distribution of fracturing fluid was concentrated between depths of 3550–4000 m, primarily within the range of 3600–3900 m. It was estimated that the reservoir fluid volume is approximately about 1.4×10^7 m^3. These findings contribute to a deeper understanding of hydraulic fracturing dynamics and reservoir characteristics, facilitating informed decision-making in resource extraction processes.

3.6. Organic Rankine Cycle (ORC) of power generation

3.6.1. Construction of ORC power generation system

The Organic Rankine Cycle (ORC) power generation system was selected for experimental power station construction, according to the project’s characteristics of extracting geothermal energy. A 340 kW trial unit and a 1200 kW generator unit set were constructed. The units adopted a cascade ORC power generation process, turbine expanders, and synchronous grid connection, meeting various needs for pilot demonstrations and scientific research. The two ORC units were arranged as a whole, using a two-stage series connection form. They can also operate independently to meet different operating conditions, effectively utilizing heat and improving power conversion efficiency.

3.6.2. Power generation tests

Construction continued in 2022, including pipeline insulation, and preparations for the operation of the 1200 kW ORC power generation unit. After the geothermal water extraction stabilized, the megawatt-level unit was connected to the electricity grid. In 2021, the 340 kW ORC power generation grid test was conducted. In 2022, another test with a 340 kW ORC unit was conducted, followed by a 1200 kW ORC unit power generation grid test. The peak power output in 2022 has increased by 25%, and the average power output has nearly doubled compared to 2021. However, due to the completeness and time constraints of the project, further testing and reservoir modifications are needed to increase power output gradually.

3.7. Induced seismicity prediction and mitigation

Induced seismicity has led to the suspension of some international HDR development projects. How to control the induced seismicity within an acceptable low level has become a significant scientific and engineering issue faced by each HDR development project. The Gonghe HDR project site is relatively close to the town, and seismic events larger than M_L 1.5 are sensible to some residents. Since 2019, 59 sensible induced seismic events have been recorded. The level of induced seismicity was normal and fell within the prediction range of mainstream prediction models (Fig. 11).

To better address the issue of induced seismicity, a specific environmental geological survey was conducted at

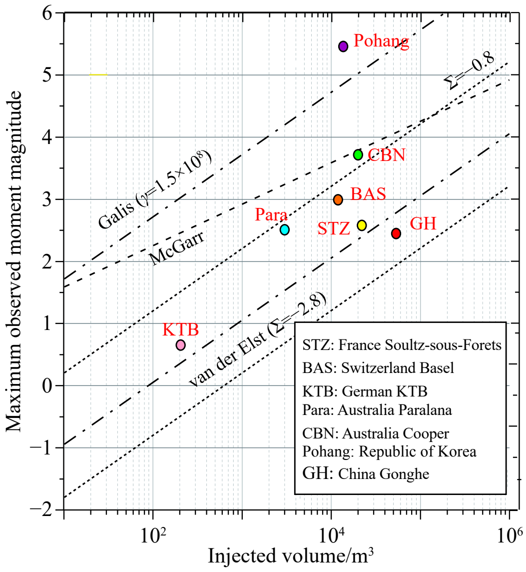


Fig. 11. Comprehensive prediction of maximum magnitude.

the start of the project, focusing on seismicity sensitive points such as residential buildings and unstable slopes around the site. By characterizing the induced seismicity level at the site, thresholds for decision-making have been determined. Based on the mechanism of induced seismicity, the injection pressure at the wellhead has been limited. At the same time, seismicity risks have been comprehensively analyzed using various methods such as stress field evolution analysis, qualitative solid-fluid coupling numerical simulation of faults, calculation of seismic activity param, analysis of fault activation conditions, statistical prediction, and physical prediction modeling. This leads to a forward-looking Traffic Light System for mitigation induced seismicity. Relying on an established high-precision near-real-time comprehensive monitoring platform for induced seismicity, the mechanism of induced seismicity and the relationship between seismic events and injection param has been analyzed in real-time. Comprehensive and efficient regulatory measures have been taken, including limiting wellhead pressures, adjusting hydraulic injection rate, maintaining low-magnitude seismic release, and soft shut-in. These measures have successfully maintained the magnitudes of induced seismicity in the Gonghe HDR project site within the red-light threshold, ensuring HDR’s safe and efficient development.

4. Conclusions

Over continued efforts from 2019 to 2022 in the Gonghe Basin, a comprehensive technical system for the entire process of HDR exploration and production was basically established, during which, many significant technological challenges were overcome, such as high-temperature drilling, large-scale reservoir construction, inter-well connectivity and circulation, heat extraction and power generation. Significant breakthroughs were achieved in the following areas:

(i) Two power generation tests from HDR were completed, confirming the feasibility of ORC power generation equipment, and many param were collected for present and future research.

(ii) The study suggests that the heat source in the Gonghe Basin is mainly from three aspects: radiogenic heat production from regional rock bodies, heat accumulation due to thermal dome activity, and heat generation from continuous dynamic shear friction within the crust.

(iii) A well group was constructed including 1 vertical well over 4000 m, 4 direction wells over 4000 m and 1 branch well. Directional fracturing technology for HDR was developed, effectively controlling fracture direction and propagation. Interwell connectivity and flow tests were conducted and the injection and production efficiency were improved. A lot of equipment for HDR exploration has been developed.

(iv) Seismic monitoring technology was implemented during the HDR fracturing, enabling real-time monitoring of induced seismic, dynamic risk assessments, and fracturing parameter adjustments. An innovative time-frequency electromagnetic prospecting system was established to obtain micro-seismic responses and fracture propagation characteristics.

The exploration and evaluation of HDR has been carried out, and the project has achieved HDR power generation tests. However, there are still many challenges that need to be overcome, such as HDR genesis under complex geological backgrounds, high precision geophysical methodology for HDR exploration and reservoir characteristics, much more efficient drilling equipment and skill, efficiency and safety engineering measurement for reservoir construction, induced seismicity mitigation, multi-field coupled numerical simulation, sustainable injection, and production, etc. It demands further research to realize the commercial development of HDR.

CRediT authorship contribution statement

Er-yong Zhang conceived of the presented idea, wrote and reviewed the manuscript. Dong-guang Wen, Gui-ling Wang prepared and reviewed the manuscript. Xian-peng Jin, Lin-you Zhang, Hai-dong Wu, Sheng Lian, Li-sha Hu, Gui-lin Zhu, Xing-long Xie, Bin Wu, Dan Wang, Xue Niu, Zhao-xuan Niu, Hui Zhang, Wen-hao Xu, Shu-qing Yao, Li Yang wrote and edited the manuscript. All authors contributed to the implementation of the project, discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

Acknowledgement

Funded by the “I*nvestigation and Evaluation of the Hot Dry Rock Resources in the Guide-Dalianhai Area of the Gonghe Basin, Qinghai*” (DD20211336, DD20211337, DD20211338) and “*Hot Dry Rock Resources Exploration and Production Demonstration Project*” (DD20230018) of the

China Geological Survey. Sincerely thank the Institute of Geophysics, China Earthquake Administration, and other scientific research institutions for their participation and support, as well as Jilin University and other universities, the China Petrochemical Corporation, and other enterprises.

References

Ayling BF, Hogarth RA, Rose PE. 2016. Tracer testing at the Habanero EGS site, central Australia. Geothermics, 63, 15–26. doi: 10.1016/j.geothermics.2015.03.008.

Baisch S, Weidler, R, Vrs R, Wyborn D, Graaf LD. 2006. Induced Seismicity during the Stimulation of a geothermal HFR Reservoir in the Cooper Basin, Australia. Bulletin of the Seismological Society of America. 96 (6), 2242–2256. doi:10.1785/0120050255.

Bruno MS, Detwiler RL, Lao K, White A, Elkhoury JE. 2012. Advanced Horizontal Well Recirculation Systems for Geothermal Energy Recovery in Sedimentary and Crystalline Formations. Office of Scientific and Technical Information Technical Reports. doi:10.2172/1057293.

Cladouhos TT, Petty S, Swyer MW, Uddenberg ME, Grasso K, Nordin Y. 2016. Results from Newberry Volcano EGS Demonstration, 2010–2014. Geothermics, 63(Sep.), 44–61. doi: 10.1016/j.geothermics.2015.08.009.

Feng YF, Zhang XX, Zhang B, Liu, JT, Wang YG, Jia DL, Hao LR, Kong ZY. 2018. The geothermal formation mechanism in the Gonghe basin: Discussion and analysis from the geological background. China Geology, 1(3), 331–345. doi: 10.31035/cg2018043.

Gan HN, Wang GL, Lin WJ, Zhang W, Qin X, Zhang C. 2020. Research on the status quo of environmental geology impact of enhanced geothermal system and countermeasures. Journal of Geomechanics, 26 (2), 211–220. doi:10.12090/j.issn.1006-6616.2020.26.02.020. (in Chinese with English abstract)

Gao J, Zhang H, Zhang H, Zhang S, Cheng Z. 2020. Three-dimensional magneto telluric imaging of the SE Gonghe basin: Implication for the orogenic uplift in the northeastern margin of the Tibetan plateau. Tectonophysics, 789, 228525. doi: 10.1016/j.tecto.2020.228525.

Ghassemi A, Kelkar S, McClure M. 2015. Influence of fracture shearing on fluid flow and thermal behavior of an EGS reservoir-geothermal code comparison study. Fourtieth Workshop on Geothermal Reservoir Engineering, 26–28.

Jeanne P, Rutqvist J, Rinaldi AP, Dobson PF, Walters M, Hartline C, Garcia J. 2015. Seismic and aseismic deformations and impact on reservoir permeability: The case of EGS stimulation at the Geysers, California, USA. Journal of Geophysical Research: Solid Earth, 120(11), 7863–7882. doi: 10.1002/2015JB012142.

Jia L, Hu D, Wu H, Zhao X, Chang P, You B, Zhang M, Wang C, Ye M, Wu Z. 2017. Yellow River terrace sequences of the Gonghe–Guide section in the northeastern Qinghai–Tibet: Implications for plateau uplift. Geomorphology, 295, 323–336. doi: 10.1016/j.geomorph.2017.06.007.

Jiang G, Hu S, Shi YZ, Zhang C, Wang ZT, Hu D. 2019. Terrestrial heat flow of continental China Updated data set and tectonic implications. Tectonophysics, 753, 36–48. doi: 10.1016/j.tecto.2019.01.006.

Kalinina EA, McKenna SA, Hadgu T, Thomas SL. 2012. Analysis of the effects of heterogeneity on heat extraction in an EGS represented with the continuum fracture model. Thirty-Seventh Workshop on Geothermal Reservoir Engineering.

Kelkar S, Woldegabriel G, Rehfeldt K. 2016. Lessons learned from the pioneering hot dry rock project at Fenton Hill, USA. Geothermics, 63, 5–14. doi: 10.1016/j.geothermics.2015.08.008.

Kim KH, Ree JH, Kim YH, Kim S, Kang SY, Seo W. 2018. Assessing whether the 2017 M_w 5. 4 Pohang earthquake in South Korea was an induced event. Science, 360(6392), 1007–1009. doi: 10.1126/science.aat6081.

Lu R, Xie WP, Liu B, Zhang SS, Zhu JS, Lin WJ. 2024. Geothermal fluid chemistry and isotope for interpreting the formation of complex geothermal system in the Gonghe Basin, northeastern Tibetan Plateau. Journal of Hydrology, 633, 130813. doi: 10.1016/j.jhydrol.2024.130813.

Kuriyagawa M, Tenma N. 1999, Development of hot dry rock technology at the Hijiori test site. Geothermics, 28, 627–636. doi:10.1016/S0375-6505(99)00033-4.

Norio T, Shun I , Isao M. 1998. Development of hot dry rock technology at Hijiori test site program for a long-term circulation test. Energy Sources, 20, 753–762. doi: 10.1080/00908319808970095.

Pollack A, Horne R, Mukerji T. 2021. What are the challenges in developing enhanced geothermal systems (EGS)? Observations from 64 EGS Sites/Proceedings World Geothermal Congress 2021.

Qiang M, Jin Y, Liu X, Song L, Li H, Li FS, Chen FH. 2016. Late Pleistocene and Holocene aeolian sedimentation in Gonghe basin, northeastern Qinghai-Tibetan Plateau: Variability, processes, and climatic implications. Quaternary Science Reviews, 132, 57–73. doi: 10.1016/j.quascirev.2015.11.010.

Tester JW, Anderson BJ, Bachelor AS, Blackwell DD, DiPippo R, Drake EM. 2006. The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century. 1–34.

Wang ZG, He ZX, Qin JC, Wang ZH, Zhang L, Zhang YF. 2016. New progress and application effect of time-frequency electromagnetic technology. Oil Geophysical Prospecting, 51, 144–151 (in Chinese).

Warpinski NR, Mayerhofer MJ, Vincent MC, Cipolla CL, Lolon EP. 2009. Stimulating unconventional reservoirs: Maximizing network growth while optimizing fracture conductivity. Journal of Canadian Petroleum Technology, 48(10), 39–51. doi: 10.2118/114173-MS.

Wassing BBT, Gan Q, Candela T. Forkker PA. 2021. Effects of fault transmissivity on the potential of fault reactivation and induced seismicity: Implications for understanding induced seismicity at Pohang EGS. Geothermics, 91, 101976. doi: 10.1016/j.geothermics.2020.101976.

Wen DG, Zhang EY, Wang GL, Zhang LY, Wang H, Zhang SQ, Ye CM, Wang WS, Jin XP, Liu DL, Jia XF, Li ST, Wu HD, Lian S, Feng QD. 2023. Progress and prospect of hot dry rock exploration and development. Hydrogeology and Engineering Geology, 50(4), 1–13. doi: 10.16030/j.cnki.issn.1000-3665.202304011.

Xu TF, Hu ZX, Li ST, Jiang ZJ, Hou ZY, Li FY, Liang X, Feng B. 2018. Enhanced geothermal systems: International developments and Research Status of China. Acta Geologica Sinica, 92(9), 1936–1947. doi: 10.3969/j.issn.0001–5717.2018.09.012.

Zhang C, Hu S, Zhang S, Li S, Zhang, L, Kong Y, Zuo Y, Song R, Jiang G, Wang Z. 2020. Radiogenic heat production variations in the Gonghe basin, northeastern Tibetan Plateau: Implications for the origin of high-temperature geothermal resources. Renewable Energy, 148, 284-297. doi:10.1016/j.renene.2019.11.156.

Zhang C, Huang RH, Qin S, Hu SB, ZH SS, Li ST, ZH LY, Wang ZT. 2021. The high-temperature geothermal resources in the Gonghe–Guide area, northeast Tibetan plateau: A comprehensive review. Geothermics, 97, 102264. doi: 10.1016/j.geothermics.2021.102264.

Zhang EY, Wen DG, Wang GL, Yan WD, Wang WS, Ye CM, Li XF, Wang H, Tang XC, Weng W, Li K, Zhang CY, Liang MX, Luo HB, Hu HY, Zh W, Zhang SQ, Jin XP, Wu HD, Zhang LY, Feng QD, Xie JY, Wang D, He YC, Wang YW, Chen ZB, Cheng ZP, Luo WF, Yang Y, Zhang H, Zha EL, Gong YL, Zheng Y, Jiang CS, Zhang SS, Niu X, Zhang H, Hu LS, Zhu GL, Xu WH, Niu ZX, Yang L. 2022. The first power generation test of hot dry rock resources exploration and production demonstration project in the Gonghe basin, Qinghai Province, China. China Geology, 5, 372−382. doi: 10.31035/cg2022038.

Zhu YQ, Li DQ, Zhang QX, Zh X, Liu ZJ, Wang JH. 2022. Characteristics of geothermal resource in Qiabuqia, Gonghe basin: Evidence from high precision resistivity data. Ore Geology Reviews, 148, 105053. doi: 10.1016/j.oregeorev.2022.105053.