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# Evaluating System and Indicators Analysis of EGS Geothermal Project in Eastern China

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## ABSTRACT

Enhanced geothermal system (EGS) is recognized as an important way to extract heat from the hot dry rock（HDR）, a high-temperature (above 180℃) and low-permeability granite containing very few fluids. In the exploration of HDR geothermal resources by EGS, site selection is one of the most crucial steps leading to the ultimate success. Based on available data from several EGS geothermal projects worldwide, we summarized key indicators to assess potential EGS sites. We also analyzed existing site selection criteria created by other research organizations in China, and designed a site evaluation system for EGS demonstration projects, adapted to the unique geological and geothermal features in Eastern China. The evaluation system is divided into 3 classes and 4 categories with a total of 14 indicators and the weight coefficients are assigned to each indicator.

## 1 INTRODUCTION

Actual construction of the world's first HDR geothermal reservoir was begun at Fenton Hill at the Los Alamos National Laboratory's Fenton Hill HDR test site in 1974(Brown D,1995).

According to the energy industrial standard NB/T 10097-2018(Geothermal Energy Terminology) issued by National Energy Administration, China, hot dry rock is defined as the rock that contains no or little fluid and has a temperature above 180℃, and the geothermal energy within it can be used under the current technical and economic conditions

Enhanced Geothermal System(EGS) is deemed as a key method of geothermal energy exploitation from HDR, which has the advantage of accessing abundant heat through injecting fluid at high pressure to create fractures in the hot rocks. The main steps for the exploitation of EGS are as follows: (1) resource exploration and assessment; (2) drilling of injection and production wells; (3) creation of a fracture reservoir; (4) making an efficient injection-production cycle to extract heat; (5) building a power plant; and (6) maintenance of the EGS project.

The geothermal energy available from HDR is clean, renewable and potentially enormous and it is gaining popularity in many countries. Among them, the US, the UK, Australia and Japan have carried out the potential evaluation (Smith MC,1983; Juarez M C,2016; Center A,2010). According to theoretical calculation, geothermal energy stored in HDR reserve in the US at a depth between 3 to 10km at temperatures above 150℃ is equivalent to 500 billion tons of standard coal.

Research on HDR was carried out relatively late in China, with related studies being reported only after 2000 (RAN Hengqian,2011; YANG Fang,2012; ZENG Yuchao,2012; ZHAI Haizhen,2014). Some institutions have conducted preliminary resource potential assessments, drilled several HDR wells, and carried out EGS-related experimental and numerical simulation studies, but have not yet entered the field test stage. Due to the unique regional geodynamic background and lithospheric structure of China, the spatial distribution of geothermal resources in China is extremely heterogeneous and the resource endowment varies greatly (DUO ji,2003; SUN Zhixin,2011;LIAO Zhijie,2015;). According to China Geological Survey, geothermal resource is distributed asymmetrically, concentrated in southern Tibet, western Yunnan, western Sichuan, southeast coast, Bohai gulf and Fen-Wei graben, etc. Geothermal energy stored in HDR reserve in China at the depth between 3 to 10km at temperatures above 150℃ is equivalent to 856 billion tons of standard coal.

To develop geothermal resources using EGS technology, the first step is to select target areas on the basis of the resource potentials, geological risk analysis, as well as technical and economic feasibility study, then conduct field tests in due course, and further explore the feasibility of conducting large-scale resource development. Selecting a promising EGS project site is one of the most crucial steps leading to ultimate success for the exploration of HDR geothermal resources.

Various studies have presented criteria for selecting EGS sites, yet there is no research focused on Eastern China where a large amount of geothermal energy is untapped. Thus, a novel evaluation system targeted at EGS sites in Eastern China is created by ENN Deep Geothermal Technology Center, based on our statistical analysis of several EGS projects worldwide and previous study carried out by other research institutes.

## 2 STUDY OF GEOTHERMAL CHARACTERISTICS OF TYPICAL EGS PROJECTS

### 2.1 FORGE EGS project in the US

The Frontier Observatory for Research in Geothermal Energy (FORGE) is an underground laboratory for developing, testing andaccelerating breakthroughs in EGS development, which locates its experimental projects in Utah area with high geothermal anomaly.

Opal Mound Fault is around 3km away in the east of well 58-32, which separates well 58-32 in the west from hot spring and fractures developed area in the east (Simmonss,2016;ZHANG Sengqi,2019). Some key figures about the well 58-32: (1) penetration of granitic basement reaches 1323m, (2) bottom hole temperature is 199℃□(3) low permeability□<30mD□, (4) the maximum stress in vertical direction is 25.6kPa/m, the minimum stress in horizontal direction is 14 kPa/m, and the medium stress in horizontal direction is 17.4 kPa/m. The FORGE program is focused on R&D of HDR without fracture and water, which requires enormous investment and is technically difficult, however, it offers great opportunity to identify a replicable, commercial pathway to EGS.

### 2.2 Soultz EGS project in France

The Soultz site is located within the Upper Rhine Graben (URG), which is a Cenozoic rift structure belonging to the West European Rift System. Younger sedimentary rocks are unconformable onto the Paleozoic basement rocks which mainly include monzogranite and two-mica granite (Pauwels H ,1997;Koelbel T,2017). The terrestrial heat flow value is about 150 $mW/m^2$ near the surface, less than 25 $mW/m^2$ at 2000m-3000m, and exceeds 70$mW/m^2$ below 4000m. Many shallow oil and gas wells have been measured to reach temperatures of around 100°C at 1000 m. From the Soultz project, the key learning is to improve geothermal reservoir flow capability through fracturing the poor quality reservoir zone (area III).

### 2.3 Habanero EGS project in Australia

For Habanero EGS project in Cooper basin, four wells have been drilled at the Habanero site to depths exceeding 4,200 m and all four wells have penetrated a major fault. The temperature in the reservoir has been measured at 244°C at ~4,220 m below the surface(Heinz-Gerd Holl,2015). The fault is a thrust type and is characterized by onshore subduction compressibility.

The overlying residual sediments of Mesozoic Jurassic and Permian is oil-gas bearing layers for the HDR project in its deeper basement, fracturing was carried out to generate lots of fractures. However, the result of outflow from fractures was far less than engineer expected. The geothermal project was forced to stop due to the quick decline outflow capability year by year.

### 2.4 Gonghe EGS project in China

The EGS Project of the Gonghe Basin is in the Chabcha region, Qinghai Province, and there exists two sequences of Cenozoic strata and basement granites. The Gonghe Basin is a rift basin with deep heat sources. From gravity and electromagnetic exploration data, it shows low-velocity and high-conductivity anomalous bodies with multi-stage distribution in lateral direction characteristics.

Formation of the Chabcha area is largely controlled by boundary fractures due to orogeny, and hot springs (60-80°C) are exposed in the vicinity of the fractures. The data from exploratory wells GH-1 and GR-1 show that the granite lithology of the basement granite is medium to coarse-grained granite with a longitudinal development from acidic to alkaline. The upper zone from 1300m to 2800m developed fractures and a few fissure belts bearing water zone. As for the deeper zone below 3000m, the lithology has the characteristics of HDR. The well cores show medium-coarse with porphyritic texture, and with joints and fissures developed locally. The rock was filled with vein or material but without water.

Based on the analysis of typical HDR projects mentioned above, six key indicators for an ideal EGS site are proposed:

⑴ High terrestrial heat flow value and high geothermal gradient;

⑵ Granitoid basement;

⑶ Coexistence of hot dry rock and wet rock

⑷ Low permeability;

⑸ Area with tensile stress;

⑹ At least 2-3Km between the targeted EGS site and the fault

## 3 SOME PREVIOUS EVALUATION SYSTEM FOR EGS PROJECT SITE SELECTION IN CHINA

Although the selection criteria for EGS projects are seldom mentioned, large amounts of basic geological and exploration data are publicly available. In addition, several indicator systems have been built by Chinese research organizations like Chinese Academy of Science, Chinese Academy of Geological Science, and SINOPEC.

Based on their own accumulation of geothermal data, the Chinese Academy of Sciences proposed the establishment of an EGS sites evaluation system based on the principles of systematicity, scientificity, comparability and quantifiability, containing a total of 18 indicators in 40 index layers (PANG Zhonghe,2020) (Table 1).

This evaluation system proposes primary and secondary indicators, and the framework is worthy of reference, yet there are the following shortcomings: (1) The interrelationship and of single indicators need to be improved: for example, drilling risk, which should be considered as exploration risk, drilling risk and fracturing risk in the actual EGS engineering; another example is the repeated assessment of drilling depth and HDR depth; (2) some factors are not closely related with EGS engineering: for example,

among the resource indicators, the terrestrial heat flow, geothermal gradient, HDR lithology and target depth do not match well with the actual parameters for calculating geothermal resources; among the technical indicators, the drilling depth and the natural fracture development is not logically related; (3) the difficulty of fracturing cannot be comprehensively evaluated, and the fluid characteristics of EGS site cannot be distinguished.

**Table 1 Evaluation system for HDR site selection**

| Indicators | Indicators | Evaluation Level | | |
|---|---|---|---|---|
| | | Optimal | Acceptable | Unacceptable |
| Resource indicators | Terrestrial heat flow value (mW/m$^2$) | >80 | 65~80 | <65 |
| | Geothermal gradient (℃/km) | >60 | 45~60 | <45 |
| | HDR lithology | Intermediate-acid granitites with very good homogeneity ; Carbonates | Granitites and metamorphic rocks with good homogeneity | Granitites and metamorphic rocks without good homogeneity |
| | Target depth (km) | <5 | 5~7 | >7 |
| | Curie point depth (km) | <25 | 25~40 | >40 |
| | Depth of low-velocity and high-conductivity strata (km) | <20 | 20~30 | >30 |
| | Volcanic activity (Ma) | <2.48 | 2.48~23.3 | >23.3 |
| | Radioactive heat generation rate (μW/m$^3$) | >4 | 3~4 | <3 |
| | Active tectonics | Tensional | Tension-shear | Compressional |
| Technology indicators | Drilling depth (km) | <5 | 5~7 | >7 |
| | Ground stress features | Very clear | clear | unclear |
| | The degree of natural fractures development | High developed but no big fault | Developed | Undeveloped or big fault developed |
| Economy indicators | Situation of land use | Unused | Use meadow, forest, farmland and garden | Use residential and industrial area, traffic utilization and Religious land |
| | Water source supply | Can guarantee supply | Can guarantee in a coordinated and effective way | Can't guarantee supply |
| | Grid-connected generation condition | Can grid-connected | Can grid-connected in a coordinated and effective way | Can't grid-connected |
| Perspective | Drilling risk | Extremely low | Low | High |
| | Policy risk | Extremely low | Low | High |
| | EGS engineering adaption | Quite favorable | Favorable | Unfavorable |

The Institute of Hydrogeology and Environmental Geology of the Chinese Academy of Geological Sciences, with reference to the geothermal deep profile of China, selected 10 potential targets of HDR in 2015 to apply the index criteria method for rating evaluation (MA Feng, SUN Hongli et.al. 2015). A total of eight indicators were selected with reference to the site selection indicators of the EGS Demonstration Project in Newberry Volcano, and each indicator was divided into four levels, with the grade range based on the geothermal basic conditions in China and expert scoring (Table 2).

**Table 2 Criteria for evaluating HDR target sites**

| Indicator class | Terrestrial heat flow value（mW/ $m^2$） | HDR lithology | Covering layer thickness /Km | Curie point depth /km | Ground stress and active tectonics | Radioactive heat generation rate （μW/$m^2$） | Geothermal gradient (℃/km) | Local power demand |
|---|---|---|---|---|---|---|---|---|
| A | ＞100 | Granite、gr anodiorite | ＜0.3 | ＜20 | Tensional | ＞4 | ＞40 | Need sufficient electricity supply |
| B | 90～100 | Gneissic granite | 0.3～1 | 20～23 | Strike-slip | 3～4 | 35～40 | Adequate electricity supply or tourist areas |
| C | 70～90 | Tuff | 1～2 | 23～26 | Compressional | 2～3 | 30～35 | Suitable for Clean energy generation |
| D | ＜70 | The other rocks | ＞2 | ＞26 | —— | ＜2 | ＜30 | Sufficient electricity supply |
| Weight | 1 | 0.6 | 0.7 | 0.8 | 0.6 | 1 | 1 | 0.7 |

This evaluation system highlights temperature indicators, but only some of the geothermal indicators are considered for evaluation. There is a lack of consideration of the interrelationships between the indicators, and their linkage to the EGS engineering objectives. For example, the target area of the above 8 indicators are all A, which only represents the granite body with thermal anomalies, and in this case, there is no indicator for the fracturing difficulty and the drilling risk.

**Table 3 Evaluation parameters for sites in hot dry rock areas**

| Parameter | | | Range(p) | | |
|---|---|---|---|---|---|
| | | | 1ange(p) | 0.75＞P.75e | 0.5＞P.5 |
| Resource condition | Geothermal reservoir | Depth（m） | ~1000−4000 | ~44000−6000 | ＜1000<br>＞6000 |
| | | Temperature (°C) | ⩾ 200 | 150−200 | ＜150 |
| | | Property | Pore or fracture developed | Pore or fracture development unknown | Pore or fracture not developed |
| | | Lithology | Not difficult with current technology | Difficult with current technology | Very difficult with current technology |
| | Caprock | Thickness (m) | ⩾ 1000 | ~500−1000 | ＜500 |
| | | Fracture development | Fracture not developed | Fracture slightly developed in the middle | Fracture developed across the caprock |
| Engineering conditions | | Drilling | Not difficult with current technology | Slightly difficult with current technology | Very difficult with current technology, needs major improvement |
| | | Reconstruction | Not difficult with current technology | Slightly difficult with current technology | Very difficult with current technology, needs major improvement |
| | | Operation | Completely supported | Generally supported, needs improvement | Not supported, needs new construction |
| Market condition | | Geothermal demand | High demand, government support | Equal demand, unclear government support | Low demand，rejected by government |
| | | Economy | Unit price higher than coal | Unit price equal to coal | Unit price lower than coal |

Based on the research results of EGS projects worldwide and its experience of using oil and gas geological grading analysis, SINOPEC points out that the primary indicator in the EGS sites selection criteria is geothermal gradient and temperature, that is, the target site with shallow buried but high temperature hot rock is preferred. Besides, the reservoir and cap rock conditions should also

be taken into consideration. Engineering and market conditions, which affect the successful construction and operation of EGS systems and the economic and efficient use of the produced geothermal resources, are also factors that need to be included in the criteria (HE Zhiliang, ZHANG Ying et al. 2015) (Table 3).

This evaluation system is similar to the hydrocarbon reservoir and cap rocks evaluation system used in the oil and gas industry, however, it doesn't reflect the characteristics of China's geothermal sites and has few temperature indicators. For example, there is no actual drilling ground temperature data in the target area. One merit of the criteria is that it includes the difficulty coefficient of engineering construction, and we suggest the difficulty coefficient of exploration should also be considered.

For the above three criteria for EGS sites selection at present, individual geothermal factors have merits, but it fails to reflect the relations among these indictors and the whole EGS project and the engineering process, as well as the interrelationship between the individual indicators, leading to the incomplete or repeated evaluation of some elements.

## 4 EVALUATION SYSTEM FOR EGS SITES SELECTION IN EASTERN CHINA

### 4.1 The principles for EGS site selection in Eastern China

In recent years, a number of institutions and scholars in China have carried out evaluation and drilling tests for EGS sites selection (XUE Jianqiu,2013; YAN Weide,2013; ZHAO Xueyu,2015; LI Shengtao,2016; LIN Wenjing). Based on our investigation and research findings of the above three institutions, namely Chinese Academy of Sciences, Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, and China Petroleum & Chemical Corporation(SINOPEC), we proposed the following basic principles for the selection of EGS demonstration projects in eastern China:

（1）To choose an site with temperature anomaly: the shallower, the better for a site target.
（2）To highlight an easy hydraulic fracturing area
（3）To distinguish wet hot rock and dry hot rock.
（4）To avoid complex geological conditions to minimize engineering risks
(5) To express a basic geothermal causal relationship between each indicator

### 4.2 Evaluation system and index analysis for EGS sites selection

In view of the characteristics of geothermal resources in eastern China, the key indicators for describing geothermal resources are the hot rock temperature, the state of the underground fluid, and the rock properties. An evaluation system for screening potential EGS sites in eastern China is established, which is divided into 3 classes and 4 categories with 14 specific indicators (Fig. 1 and Table 4).

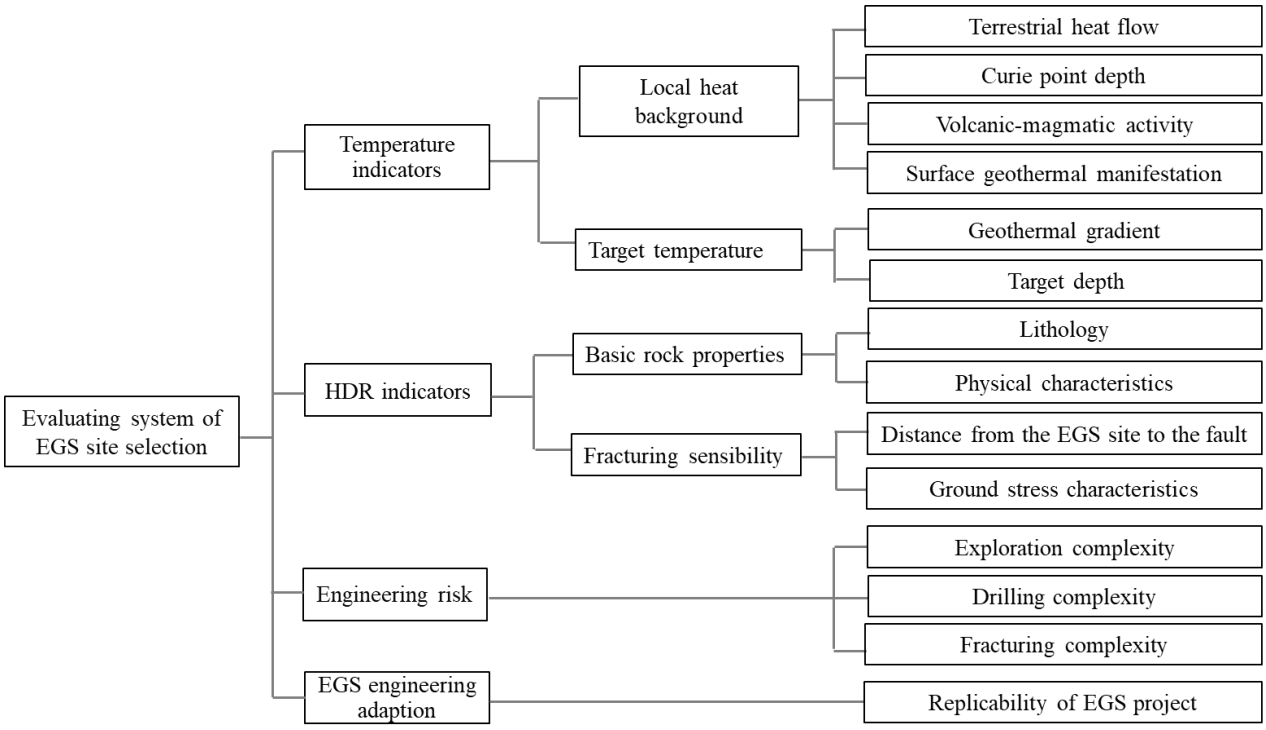


**Fig.1 Evaluation system for EGS demonstration project sites selection**

**Table 4 Evaluation system and indicators analysis of EGS project sites selection**

| No. | First-class indicators | Second-class indicators | Third- class indicators | Optimal | Acceptable | Unacceptable |
|---|---|---|---|---|---|---|
| 1 | Temperature Indicators | Local heat background | Terrestrial heat flow（ $mW/m^2$） | >75 | 61~75 | <60 |
| 2 | | | Curie point depth (km) | <20 | 20~25 | >25 |
| 3 | | | Volcanic-magmatic activity | During the Himalayan Orogeny (<65 Ma ) | During the Yanshan Orogeny(199.4-65Ma) | Before the Yanshan Orogeny (>199.5Ma) |
| 4 | | | Surface geothermal manifestation | Hot springs with surface temperature greater than>70°C | Hot springs with surface temperature greater than>60°C | Hot springs with surface temperature less than 60°C or not developed |
| 5 | | Target temperature | Geothermal gradient（ °C/km） | >36 | 30-35 | <30 |
| 6 | | | Target depth (km) | <4 | 4~5 | >5 |
| 7 | HDR cindicators | Basic rock property | Lithology | Isotropic medium-acid granites | Isotropic medium-acid granites | Low grade metamorphic rocks or other rock types |
| 8 | | | Physical characteristics（porosity, permeability, the degree of joints and natural fissures development） | Rock joints developed, natural fractures are closed and filled (or rock with high porosity and low permeability) | Joints undeveloped (or rock with low porosity and low permeability | Fractures developed (or rock with high porosity and high permeability) |
| 9 | | Fracturing sensibility | Distance from the EGS site to the fault (km) | >2 | 1~2 | <1 |
| 10 | | | Ground stress characteristics | Tensile stress environment with maximum stress in vertical direction and minimum stress in horizontal direction | Strike-slip stress environment with maximum and minimum stress in horizontal direction, medium stress in vertical direction | The thrust nappe structure with minimum stress in the vertical direction |
| 11 | Engineering risk | | Exploration complexity | A target with a simple subsurface structure and detailed exploration data | A target with a relatively complicated subsurface structure and relatively detailed exploration data | A target with extremely complicated subsurface structure and lack of data |
| 12 | | | Drilling complexity | No fracture zone or stratum with special lithology is found in the target area | There is a small amount of fracture zone or stratum with special lithology | A large number of special rock stratum (salt bed, gravel bed, natural fractures developed) , especially when the kickoff point in the stratum with special lithology (e.g. basalt) |
| 13 | | | Fracturing complexity | Rock with a high degree of homogeneity, normal fracture pressure and fracture extension pressure | Rock with a medium degree of homogeneity, relatively high fracture pressure and fracture extension pressure | Rock with inhomogeneous structure, extremely high fracture pressure and fracture extension pressure |
| 14 | EGS engineering adaption | | Replicability of EGS projects | Similar geological conditions are favorable for EGS project construction and replication | The complex geological conditions are relatively unfavorable for EGS project construction and replication | The unique and complex geological conditions are extremely unfavorable for EGS project construction and replication |

### 4.3 Indicators and values of evaluation system for EGS demonstration project sites selection

4.3.1 Temperature indicator

Temperature is one of the most important indicators in the evaluation of geothermal resources and potential EGS project sites, generally illustrated by local geothermal background and temperature of the targeted sites. Local geothermal background indicators consist of terrestrial heat flow, curie point depth, volcanic activity and surface geothermal manifestation, while target temperature consists of geothermal gradient and target depth.

(1) Terrestrial heat flow

The terrestrial heat flow is a direct thermal parameter that can quantitatively reflect the geothermal background of a region and is a background parameter for evaluating geothermal resources. The regional high heat flow anomalies in China: (1)Tibetan-Yunnan region in southwest China with average heat flow value of 90mW/m$^2$; (2) Eastern China with average heat flow value of 65mW/m$^2$. On the other hand, the relatively low heat flow regions include Central China with average heat flow value of 55mW/m$^2$ and northwest China with average heat flow value of 50mW/m$^2$. Considering that the targeted EGS sites in this paper is focused on the central-eastern region, the terrestrial heat flow is classified into 3 levels: ① >75 mW/m$^2$, optimal; ② 60~75 mW/m$^2$, acceptable; ③ <60 mW/m$^2$, unacceptable.

（2）Curie point depth

A Curie point isothermal surface is the bottom boundary of magnetic crust on the upper lithosphere of the earth (XIONG Shengqing,2016). The Curie point depth is inversely proportional to the heat flow, which means the shallow Curie point depth is associated with intense tectonic and magmatic activity. Given the depth distribution of Curie point in China, we classify the Curie point depth for eastern China, which generally ranges from 16 to 35km, into three levels: ①<20km, optimal; ②20~25km, acceptable; ③>26km, unacceptable.

（3）Volcanic-magmatic activity

The role of volcanic-magmatic activity in the formation of geothermal anomalies depends on the geological age of the magma intrusion, the scale of the intrusion and the insulation conditions of the overlying strata, etc. The newer the age, the more residual heat will be retained. In eastern China, there are very few volcanoes younger than the Miocene (23.3 Ma), and most of the volcanic activity occurred during the period of Yanshan movement (65-199.4 Ma). Therefore, the time of volcanic magmatic activity is classified into three levels: ①during the Himalayan Orogeny（<65Ma）is optimal; ②during the Yanshan Orogeny (65~199.4Ma) is acceptable; ③ before the Yanshan Orogeny (>199.5Ma) is unacceptable.

（4）Surface geothermal manifestation

Geothermal anomalies are sometimes characterized by surface features like hot springs, which can be classified into three levels according to the data of hot springs in China: ①hot springs with surface temperature greater than 70°C is optimal; ②hot springs with surface temperature greater than 60°C is acceptable; ③hot springs with surface temperature less than 60°C or not developed is unacceptable.

（5）Geothermal gradient

Generally, the area with geothermal gradient >3.5°C/100m is considered as a geothermal anomaly in China and the dominated heat source in central and eastern China comes from of deep strata through heat conduction, rarely from volcano-magmatic activities. The geothermal gradient value of the target area is classified into 3 levels: ①>36°C/km, optimal; ②30~35°C/km, acceptable; ③ <30°C/km, unacceptable.

（6）Target depth

Based on average geothermal gradient distribution in eastern China, the target depth of the EGS project is classified into 3 levels: <4km, optimal; 4~5km, acceptable; >5km, unacceptable.

It is noted here that the sites of EGS demonstration projects are mainly concentrated in the central-eastern part of China, so the values for temperature indicators are based on the local geologic characteristics.

4.3.2 HDR indicators

HDR indicators are used to represent artificial fracturing and flow passage characteristics in EGS projects, which consist of main physical properties and fracture sensitivity. The rock properties include lithological and physical characteristics, while physical characteristics are mainly related to the development of natural fractures. And fracturing sensibility consists of 1) distance from the EGS site to the fault and 2) ground stress characteristics.

（1）HDR lithology

HDR lithology is one of the key factors affecting artificial fracturing. Geothermal energy of exist in various of metamorphic rocks or crystalline rocks, such as granite, granodiorite, biotite gneiss and so on (Ayling B, 2013; Breede K,2013; Shyimin L,2018). The Fenton Hill EGS project is built in a Precambrian rock mass with homogeneous biotite granodiorite. While the upper part of the Soultz EGS project in France is a Paleoproterozoic-Neoproterozoic sedimentary sandstone and the lower part is a Paleozoic granite there are two sequences in generally, the upper sequence is sedimentary sandstones from Paleogene to Neogene, and the lower sequence is Paleozoic granite. Therefore, the 3-level classification scheme of the lithological evaluation of the EGS project is as follows: ①isotropic medium-acid granites are optimal; ②isotropic and medium-high grade metamorphic rocks are acceptable; ③ low grade metamorphic rocks or other rock types are unacceptable.

（2）Physical characteristics

The physical characteristics of hot dry rocks consist of porosity and permeability, but since most of the hot rock targets of EGS project are composed of low permeability granite and metamorphic rocks, then the natural fracture development conditions play a key role to the later artificial fracturing process. The natural fracture development is directly related to the degree of complexity of artificial

fracturing. Given the three factors mentioned above, physical characteristics of hot dry rocks are classified into 3 levels: ①rock joints developed, natural fractures are closed and filled (or rock with high porosity and low permeability), optimal; ② joints undeveloped (or rock with low porosity and low permeability , acceptable; ③fractures developed (or rock with high porosity and high permeability), unacceptable.

（3）Distance from the EGS site to the fault

Although the naturally developed micro-fractures are beneficial to the implementation of fracturing, larger faults in the hot dry rock may result in a short circuit in the geothermal reservoir. Meanwhile, during the fracturing process, fracturing activities with large displacement and pressure may link faults and cause induced earthquakes. Out of safety concerns and given the general design of EGS projects and the length of extended fracture, we classify the distance from the EGS site to the fault system into three levels: > 2km, a safe distance, optimal; ②1~2km, a generally safe distance, acceptable; ③ <1km, a distance that may link faults, unacceptable.

（4）Ground stress characteristics.

In recent years, large-scale hydraulic fracturing has been used worldwide to create reservoirs, which is not only the most critical step for EGS construction, but also affects directly the overall cost. Accurate understanding of the rock stress is a prerequisite for the construction of artificial reservoirs. The Cooper geothermal project in Australia was forced to shut down, partly due to inadequate analysis of ground stress, which caused poor connectivity between wells. Based on the local tectonics and statistical distribution of ground stress, the ground stress characteristics are classified into 3 levels: ①tensile stress environment with maximum stress in the vertical direction and secondary and minimum stress in the horizontal direction is optimal; ②strike-slip stress environment with maximum and minimum stress in the horizontal direction, and median stress in the vertical direction is acceptable; ③the thrust nappe structure with minimum stress in the vertical direction is unacceptable.

4.3.3 Engineering risk

The evaluation of EGS engineering risk is focused on assessing the complexity of exploration, drilling and fracturing.

（1）Exploration complexity

The geothermal anomaly area in the central-east China is a vast area with a variety of subsurface formations and strata. Based on subsurface geology and the exploration data on hand, the exploration complexity of targeted EGS sites can be classified into 3 levels: ①a target with a simple subsurface structure and detailed exploration data is optimal; ②a target with a relatively complicated subsurface structure and relatively detailed exploration data is acceptable; ③a target with extremely complicated subsurface structure and lack of data is unacceptable.

（2）Drilling complexity

Drilling risk is closely related to the stratigraphic complexity and faults distribution in target area. Based on the subsurface geology in the target area, EGS drilling complexity can be classified into 3 levels: ①it is preferred that no fracture zone or stratum with special lithology is found in the target area; ②it is acceptable that there is a small amount of fracture zone or stratum with special lithology; ③presence of a large number of special rock stratum (salt bed, gravel bed, natural fractures developed) is unacceptable, especially when the kickoff point in the stratum with special lithology (e.g. basalt).

（3）Fracturing complexity

The fracturing effect is not only related to the development of natural fractures but also the homogeneity of HDR. Rock inhomogeneity poses challenge to the drilling efforts. The more heterogeneous, the more difficult it is. According to the geology of the targeted site, fracturing complexity can be classified into 3 levels: ①rock with a high degree of homogeneity, normal fracture pressure and fracture extension pressure is deemed as optimal; ②rock with a medium degree of homogeneity, relatively high fracture pressure and fracture extension pressure is deemed as acceptable; ③rock with inhomogeneous structure, extremely high fracture pressure and fracture extension pressure is deemed as unacceptable.

4.3.4 Replicability of EGS projects

Another important criterion for a demonstration project is replicability, which mainly refers to the comparability of subsurface geothermal conditions. Based on geological conditions, it is optimal for an area where similar geological conditions are commonly distributed and its simple geologic structure allows for easier construction and replication of the demonstration project; while it is unacceptable for an area where the unique and complex geological conditions are unfavorable for project construction and replication.

### 3.4 Weight coefficient for indicators

In this evaluation system, the values of weight coefficient of all the indicators are obtained by averaging the initial scores given by a panel of experts. The total weight of indicators in each class is assigned to be 1. The final weight coefficient can be obtained by multiplying the weight of each indicator in the three classes (Table 5).

**Table 5 Weight coefficient for each indicators**

| Indicators | Weight (first-class) | First-class indicators | Weight (second-class) | Second-class indicators | Weight (third-class) | Third-class indicators | Weight (final ) |
|---|---|---|---|---|---|---|---|
| 1 | 0.48 | Temperature Indicators | 0.4 | Local heat background | 0.39 | Terrestrial heat flow value | 0.075 |
| 2 | | | | | 0.31 | Curie point depth | 0.060 |
| 3 | | | | | 0.15 | Volcanic- magmatic activity | 0.029 |
| 4 | | | | | 0.15 | Surface geothermal manifestation | 0.029 |
| 5 | | | 0.6 | Target temperature | 0.6 | Geothermal gradient | 0.173 |
| 6 | | | | | 0.4 | Target depth | 0.115 |
| 7 | 0.31 | HDR indicators | 0.5 | Basic rock properties | 0.3 | Lithology | 0.047 |
| 8 | | | | | 0.7 | Physical characteristics （porosity, permeability, the degree of joints and natural fissures development） | 0.109 |
| 9 | | | 0.5 | Fracturing sensibility | 0.42 | Distance away from fractures (km) | 0.065 |
| 10 | | | | | 0.58 | Regional stress environment features | 0.090 |
| 11 | 0.12 | Engineering risk | | | 0.4 | Exploration complexity | 0.048 |
| 12 | | | | | 0.3 | Drilling complexity | 0.036 |
| 13 | | | | | 0.3 | Fracturing complexity | 0.036 |
| 14 | 0.09 | EGS engineering adaption | | | 1 | Replicability of EGS project | 0.090 |

## 5 RESULTS OF EGS SITE SELECTION EVALUATION

Based on the site selection criteria we proposed, 14 indicators are assigned with 100, 80 and 60 points in correspondence to the three levels of “Optimal”, “acceptable” and “unacceptable” respectively, and then, multiply the initial score of an indicator by the weight coefficient to get the its final score, and the total score of geothermal targets can be obtained by accumulating the individual scores of 14 indicators.

**Table 6 Score of EGS project targets**

| EGS project target | | Final calculated score |
|---|---|---|
| FORGE | | 96.328 |
| Soult | | 92.075 |
| Habanero | | 80.926 |
| Eastern China EGS projects | Target one | 89.798 |
| | Target two | 89.162 |
| | Target three | 87.444 |
| | Target four | 82.646 |
| | Target five | 82.532 |
| | Target six | 80.726 |
| | Target seven | 73.47 |

Ten targeted EGS sites are scored and ranked according to the calculation system, which include the FORGE project in the United States, the Soultz project in France and the Habanero EGS project in Australia, and seven potential sites in eastern China (Table 6). The final results have verified the reliability and validity of evaluation system, since the scores of the three exploited EGS sites are consistent with their actual geological and geothermal conditions. Hence, it is believed that the targeted site in eastern China with the highest score is of greater potential compared to other sites.

## 6 CONCLUSIONS

(1) Based on a comprehensive study of typical EGS projects, some key indicators of EGS projects are summarized, such as temperature, HDR lithology, physical properties, ground stress field, distance from the EGS sites to the faults, etc., which laid the foundation for the proposed evaluation system for EGS demonstration projects site selection in eastern China.

(2) By analyzing the site selection criteria established by three research organizations in China, and combining the geological and geothermal conditions of eastern China, we proposed some main principles for EGS sites selection and established a comprehensive evaluation system, which is mainly applied to the selection of potential sites in eastern China.

(3) The evaluation system for site selection of EGS projects in eastern China is divided into 3 classes and 4 categories with a total of 14 indicators. The 14 indicators are given values (optimal, acceptable and unacceptable) at different scenarios, and the comprehensive weight coefficients of each indicator are calculated based on the established system and their interrelationships. The evaluation system has clear objectives and reasonable weight coefficients. We scored and ranked three EGS sites in the US, France and Australia, as well as seven potential sites in eastern China, and the final result has verified the reliability of the evaluation system and indicates that it can be used as a tool for screening potential EGS sites in eastern China.

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