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Feasibility Evaluation of EGS Project in the Xujiaweizi Area: Potential Site in Songliao Basin, Northeastern China

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ABSTRACT

Located at the junction of three tectonic plates with vast territory, China possesses abundant deep geothermal energy storage. According to the research of institute of geology and geophysics, Chinese academy of sciences, the Songliao Basin is characterized by a high regional heat flow of 50-90mW/m^2 and a high geothermal gradient of 3.9~6.5℃/100 m. The Xujiaweizi (XJWZ) area, located in the north of Songliao Basin, has a high average geothermal gradient of 40-60℃/km and possesses several features indicating potential for EGS development. Moreover, in 2012, the National High-Technology Research and Development Program (863 program) started the "HDR thermal energy development and comprehensive utilization of key technology research" project and the XJWZ area was selected to evaluate the feasibility of EGS development in the Songliao Basin.

We investigate the potential of EGS project in XJWZ by geology, geophysics and geochemistry. Geophysical exploration has discovered the crust of the XJWZ is very thin, only 29km; the presence of a high conductivity layer, thickness of 2-5km, with low resistivity and low density indicates there exists a magma chamber reservoirs which may be the heat source for the thermal anomaly; the widespread distribution of Yingcheng Formation volcanic rocks and the magma chamber may be the heat source for the thermal anomaly. In addition, the developed deep and shallow fault can be a good channel for upward transmission of deep heat hot resources. The temperature maps at different depths in XJWZ are constructed, subsurface temperature ranges from 39℃ to 60 ℃ at a depth of 1 km, from 75℃ to 140℃ at 2 km, from 108℃ to 136℃ at 3 km, and from 144℃ to 180℃ at 4 km. The Yingcheng Formation volcanic rock is the preferred reservoir rock because it is very dense and has a rich natural micro-cracks. The development of natural fracture can conduct the water fracturing like the Soultz project, which could reduce the cost. Besides, the two magma melting layer as the heat source can guarantee the running time of EGS project.

Fracture parameters, such as length, height, aperture, shape and conductivity, were obtained through real fracturing in igneous rock reservoirs of Yingcheng Formation. The heat production potential from the fractured Yingshen reservoir was numerically investigated based on the data obtained from the fracturing results and reservoir parameters. The results indicate that the hydrothermal production in a single conductive fracture from the well YS2 is approximately 10kg/s and the electricity-generating capacity is nearly 1.5MWe. Methods for improving hydrothermal production are given. We believe the horizontal wells and more cracks could generate more electric energy.

The results of the analyses described above indicate that while there will be many problems needed to be considered, the XJWZ area has the potential for EGS development.

1. INTRODUCTION

As one of renewable energy resources, geothermal energy has the advantages of great resource potential, low carbon emission, widespread distribution. Geothermal energy from Hot Dry Rock (HDR) represents a large, indigenous resource that can provide base-load electric power and heat, while incurring minimal environmental impacts **(**MIT, 2006)**.** Further, EGS provides a secure source of power for the long term that would help the country against economic instabilities resulting from fuel price fluctuations or supply disruptions in the future.

With increasing population and growing demands for energy production and consumption in China, the existing energy structure is no longer rational. Located at the junction of three tectonic plates with vast territory, China possesses abundant deep geothermal energy storage. According to the research results of Institute of Geology and Geophysics, Chinese academy of sciences in 2012, the total HDR resources distributed at depths 3-10 km in mainland China is 20.9×10^6EJ, which is equivalent to 714.9×10^{12}t of standard coal, 2% of which can be used 4,400 yr national consumption.

In spite of its enormous potential, the HDR geothermal option for the China has been ignored and there is no EGS project in China, by far. The delay in the development of HDR geothermal in China was attributed to the high initial cost and the limited technologies. However, these obstacles could be easily solved in the Oilfield, where there are many abandoned oil wells and mature fracturing technologies. The key technologies of oil and gas exploration and development, including horizontal well and hydrofracturing technology, could be directly transferred to the HDR resource development.

The development research of the HDR geothermal resource started late in China, only several institutions participated in the theory discussion of the HDR. In the recent years, the government has started to provide more policy support for HDR geothermal development from medium to longer term, such as in 2012, the National High-Technology Research and Development Program (863 program) started the "HDR thermal energy development and comprehensive utilization of key technology research" project ,which also gets the favor of the enterprise of Daqing oilfield company, and the XJWZ area was selected as the pilot to evaluate the feasibility of EGS development in the Songliao Basin.

2. REGIONAL STUDIES (SONGLIAO BASIN)

2.1 Geology

2.1.1 Geological setting

The Songliao Basin is located in northeastern China, approximately 750 km in length, 330-370 km wide, with a total area of $26\times10^4km^2$. It is a large diamond shaped Meso-Cenozoic sedimentary basin, formed on a folding basement, spreading in an NNE direction. The basin experienced a strong rift stage, a rift to depression stage, a depression stage and a depauperizing depression stage since the Jurassic Period, filled with Meso-Cenozoic terrigenous clasolite, 7000 m thick.

The structural unit of the basin was divided into six parts: central depression, northern plunge, northeastern uplift, western slope, southwestern uplift, southeastern uplift. The XJWZ is located in the central depression and the Daqing oilfield is also here (Fig.1).

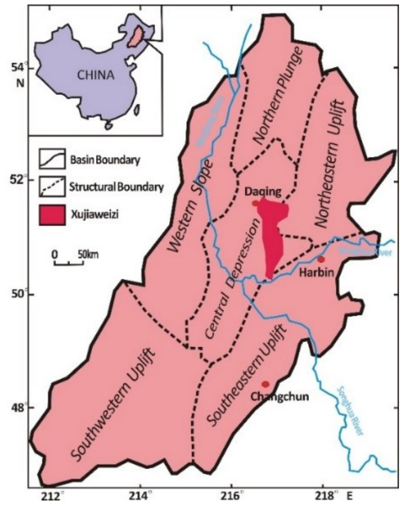


Figure 1: Location of the Songliao Basin and XJWZ showing major structure zones in the basin.

In this basin, the terrestrial strata of the late Mesozoic –Cenozoic age, which comprise volcanic, volcaniclastic and sedimentary rocks, are unevenly distributed across the basin. The basement mainly consists of the middle Jurassic granites and Paleozoic strata. The Upper Jurassic and Cretaceous strata in the basin consist of ten lithologic formations, from bottom to top including Huoshiling (J3h), Shahezi (K1s) , Yingcheng (K1y), Denglouku (K1d), Quantou (K2q), Qingshankou(K2qn), Yaojia (K2y), Nenjiang (K2n), Sifangtai (K2s) and Mingshui(K2m) Formations. The Mesozoic strata are unconformably overlied by Cenozoic strata, such as the Yi'an (E2y), Da'an (N1d) or Taikang (N2t) Formations, or Quaternary sediments. Fig 2 shows the stratigraphic cross sections through the Songliao Basin.

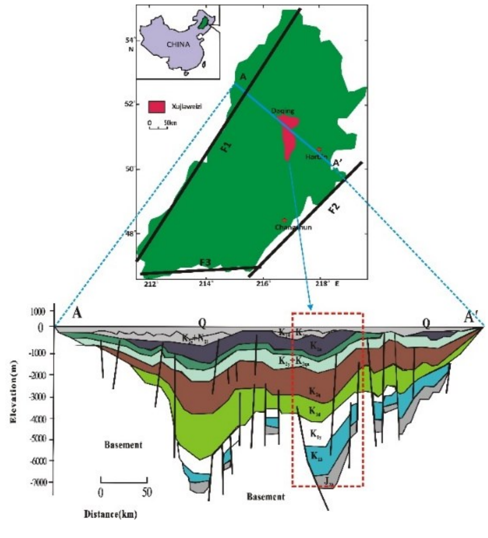


Figure 2: Stratigraphic cross sections through the Songliao Basin (A–A′) as well as the location of the XJWZ.

2.1.2 Tectonics

The basin is located on the Mongolia –North China plate within the eastern Central Asian Orogenic Belt (CAOB) (P.J. Wang et al., 2006).The CAOB formed by progressive subduction of the Paleo -Asian Ocean and amalgamation of terranes of different types and derivation , and is specifically marked by its massive juvenile crustal production during the Phanerozoic (Rojas-Agramonte et al., 2011). In a more regional context, the study area belongs to the mobile belt between the Siberian craton in the north and the Sino-Korean (North China) craton in the south (Fig. 3). Pre- and syn-tectonic evolution of the Song liao basin was characterized by three successive tectonic stages including (1) the closure of the Paleo-Asian Ocean during the Paleozoic, (2) subduction and closure of the Mongol-Okhotsk Ocean during the Late Paleozoic-Mesozoic and (3) the subduction of the Paleo-Pacific Ocean during Mesozoic –Cenozoic times (Wu et al., 2001).

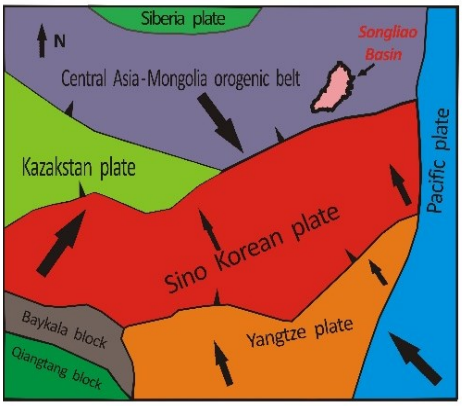


Figure 3: Plate position and tectonic stress field of Songliao Basin and adjacent areas.

2.1.3 Deep fault

The Songliao Basin is located in the Song-liao fault fold belt which belongs to the Tianshan-Qilian-Great Xing'an fault fold series, and there exist three crust cutting deep faults: the NE and NNE Sunwu-Shuangshen fault, Taikang-Beizhen fault and NW fault (Fig.4). In XJWZ fault depression, the Xuxi fault and Songxi fault firstly cut through the basement, then the strong geological tectonics activity and the followed magmatic activity cause the high geothermal field in XJWZ area. The deep fault could cause the corresponding rise of the moho surface and then make the upper mantle intrude into the crust, so the magma reservoir is formed in the crust, which make the whole basin have a high geothermal field. Besides, the radioactive substances exist in upper mantle ,the deep fault become a upwelling channels of the mantle source material and the heat supply center area of the radioactive substances.

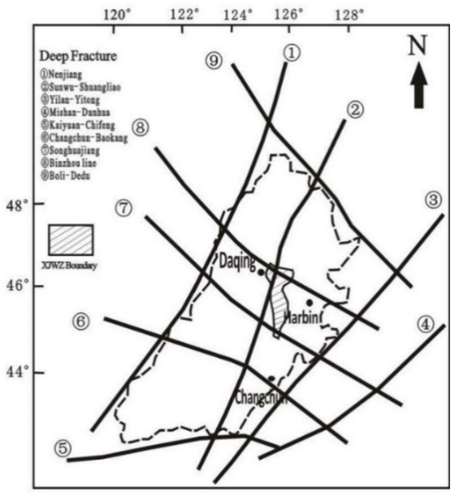


Figure 4: Schematic map of deep fault in Songliao Basin.

2.1 Geology

2.2.1 Moho and Curie-surface

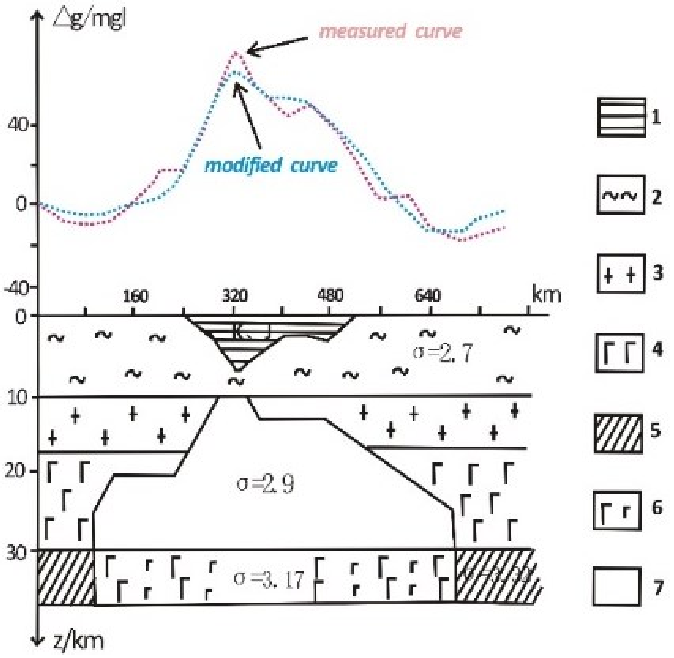
The buried depth and distribution of moho directly control the geothermal field of the Songliao Basin. The Songliao Basin has a thinner crust , whose moho is located in 29-33km.The most shallow moho is in XJWZ area with a depth 29-30km, so the XJWZ owns the highest temperature of the basin. Besides, the Curie-point surface depth of Songliao Basin is 10-24km and the most shallow place is still in XJWZ area about 10-12km.

2.2.2 Gravity and Magnetics field

The bouguer gravity anomaly value of the Songliao Basin ranges from -30~+16 mgal. In general, the highest gravity value distributes in the center and the lowest value distributes at the edges of the basin. Local anomaly area is small and high amplitude anomaly phenomena are relatively more.

The magnetic field changes significantly and has many anomalies. The direction of the magnetic field lines is main NE trend. The change of the magnetic field also has obvious zoning characteristics, which has a good corresponding relation with the change of the geothermal field. In the center of the basin with high geothermal field, the gravity-magnetics field has an extensive gradual change and at the edges of the basin with low geothermal field, the gravity-magnetics field has high amplitude change in small area.

According to the gravity profile of the Luhin sum-Tailai-Harbin-Jixi and the other geophysical data, the crust structure model of Songliao graben basin is builded as shown in Fig.5.



1-cenozoic sedimentary rock;2-metamorphic basement;3-granite layer;

4-basaltic layer;5-mantle;6-anomalous mantle;7-mantle-derived basalt

Figure 5: Crust structure model of Songliao graben basin.

2.2.3 Magma

According to drilling data, deep geophysical detection results and comprehensive interpretation of Manzhouli-Suifen river section (Fig.6), the crustal thermal structure model of Songliao Basin is set up. There exists a high conductivity layer, thickness of 2-5km, with low resistivity and low density. The high conductivity layer may be a magma chamber caused by the mantle intruding the crust through the deep fracture.

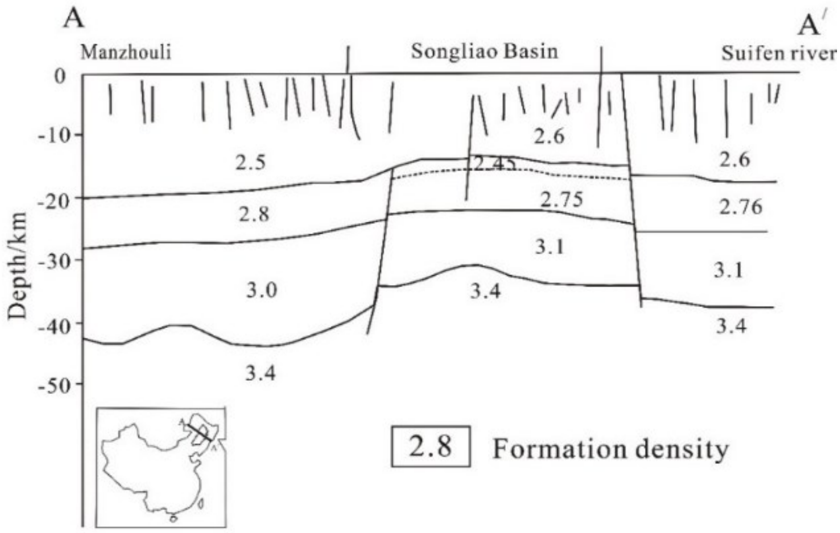


Figure 6: Schematic map of Manzhouli-Suifen river crust structure section.

2.1 Geology

2.3.1 Heat flow

According to the terrestrial heat flow test, the heat flow of the Songliao Basin arranges from 26. 52 to 79. 3 mW•m- 2 and the average value is 71.36 mW•m- 2, which is greater than the global average value of 66 mW•m- 2. The distribution characteristics of the Songliao Basin approximately is high in the central and low on the edge of the basin.

2.3.2 Geothermal gradient

On the whole, the central Songliao Basin possesses a high geothermal gradient of 3.0-5.0℃/100m, which reduces outside in turn. The geothermal gradient decreases with depth, and the borehole temperature data in the central basin show that the geothermal gradient is 4.8℃/100m in 1000-2000m;the geothermal gradient is 3.0℃/100m under the 2500m, mainly because the rock density increases, the porosity decreases and thermal conductivity increases with the increase of the depth.

3 LOCAL STUDIES (XJWZ AREA)

From the results discussed above, we can conclude that :1) the XJWZ area is located above the thinnest crust of the Moho and Curie-surface in the Songliao Basin; 2) the XJWZ area possesses the highest geothermal gradient and temperature of the Songliao Basin; 3) there exists a mantle high-conductive layer under the XJWZ area which may be the heat source to support a sustainable heating. Taken together, the results prove that the XJWZ is the most suitable area for the EGS development in the Songliao Basin.

The XJWZ was divided into two parts: upper depression layer and lower fault depression. The upper depression layer includes five group formation, such as Sifangtai group, Nenjiang group, Qingshankou group, Quantou group and Denglouku group, the total thickness of which is about 3000-5000m. The lower fault depression is the target reservoir for the development of the HDR, mainly including the Yingcheng group, Shahezi group and Huoshiling group.

3.1 Geological and tectonic features

The XJWZ is located on the XJWZ-Beian fault depression belt in northern Songliao Basin. It is nearly ns-trending distribution and it measures 90km long by 55km at its widest point. The XJWZ covers an area of 5400 km2, formed in the late Jurassic to early cretaceous, is a larger fault depression in northern Songliao Basin. The area has many gas fields and many natural gas drilling.

3.1.1 Sedimentary characteristics

XJWZ fault depression mainly include Yingcheng group, Shahezi group and Huoshiling group from top to bottom (Fig.7).

1) Yingcheng group

Better development, wide distribution. Main lithology includes rhyolite, tuff, andesite and sand shale.

2) Shahezi group

Main lithology includes mudstone and conglomerate.

3) Huoshiling group

Main lithology includes middle-basic volcanic rocks (top and bottom) and clastic rocks (middle).

Stage		Group	Unit	Map Symbol	Thickn -ess(m)	Geological age	Lithological characteristics and sedimentary structures
Mesozoic	Lower Cretaceous	Quantou	4	K_1q	0~128		The upper part of gray, black mudstone and gray-green, gray siltstone, shale and siltstone, etc. ranging from thick interbedded Central to purple-red mudstone mainly folder gray-green,Zihui, off-white powder,fine-grained sandstone.The lower part is brown purple mudstone and gray, purple sandy conglomerates interbedded, partial clip a small amount of tuff
			3		0~692		
			2		0~479		
			1		0~855	112Ma±	
		Denglouku	4	K_1d	0~170		The upper part of gray-green, gray-brown mottled sandy conglomerate interbedded with mudstone.The lower gray,mottled sandy conglomerate folders purple,dark gray shale and a little tuff
			3		0~560		
			2		0~700		
			1		0~100	124Ma±	
		Yingcheng	4	K_1yc	10~400		The upper part of the acidic volcanic rocks,pyroclastic rocks and sandstone, siltstone, black mudstone.The middle part is mainly dark shale containing coal seams, Ansan lower basalt,volcanic breccia, tuff and light gray sandstone, sandy conglomerate clip seam
			3		0~780		
			2		0~300		
			1		0~1600	130Ma±	
		Shahezi	4,3	K_1sh	0~745		Dark gray, gray-black shale,clip white sandstone,siltstone and minor tuff,local folders coal line
			2,1		0~615	145Ma±	
		Huoshiling	2	K_1h	0~1000		Tuff, andesite,tuffaceous breccia, basalt,and tuffaceous conglomerate
			1		0~500		
Underlying altered Jurassic volcanic rocks group							

Figure 7: Comprehensive column map of the stratigraphy of the Lower Cretaceous Epoch in the XJWZ fault depression

3.1.2 Structural history

Late Jurassic, the XJWZ fault depression began to deposit under the action of tensile stress. With the aggravation of the tensile stress and action of the deep fault, strong volcanic eruption occurred and a set of middle-basic volcanic rocks is formed in the XJWZ fault depression area. Then, the basin experienced a large scale tension, which expanded the region of the basin and many lakes, forming a broad fault depression lake basin, and the Shahezi group began to deposit. After the deposition of the Shahezi group, Huoshiling group and Shahezi group suffered a fold reversal , due to the partial strong extrusion, and the uplift made the Shahezi group suffered a serious erosion in this area. During the Yingcheng group sedimentary period, the basin entered the stage of fault-depression transformation. In 135.0 Ma, the crust suffered a tension, which caused the deep fracture again strong activity and a volcanic eruption, hence, a widely distributed acidic volcanic rocks are formed in the XJWZ fault depression.

XJWZ fault depression has experienced many times of tension-extrusion tectonic movement, forming the favorable conditions of reservoir and caprock. Deep fault, the magmatic eruption channel and geothermal migration channel, is of great significance to the exploitation of geothermal resources.

3.2 Geothermal field

3.2.1 Geothermal temperature and gradient

The research of the XJWZ temperature distribution is based on the data from the oil and gas testing. In the paper, the bottom hole temperature measurement data is counted from more than 20 deep wells over 4000m depth over the XJWZ area (Table 1).

Table 1: The temperature data of the deep exploratory well in XJWZ.

No.	Well	Depth（m）	Temperature（℃）	Formation
1	YS-1	4800	164.8	Jhs
2	YS-2	5520	183	K1hs
3	XS-22	5320	172	K1yc
4	XS-3	4763	165	K1yc
5	XS-41	5453	162.65	K1yc
6	XS-7	4510	161	K1yc
7	XS-19	4257	160	K1yc
8	XS-401	4546	159	K1sh
9	XS-502	4361	156	K1yc
10	XS-CP11	4020	155	K1yc
11	ZS-14	4650	154	Jhs
12	XS-13	4450	153	K1sh
13	FS-15	4400	153	K1sh
14	FS-10	4280	153	basement
15	DS-1	4650	152	K1sh
16	XS-9	4311	152	K1yc
17	XS-201	4333	151	K1yc
18	CS-8	4352	150.2	basement
19	XS-301	4370	150	K1yc
20	XS-8	4228	150	K1sh

The temperature data has certain correlation with depth according to statistical regression analysis. To the temperature and geothermal gradient, there exists a turning point in the fault-depression transition, which indicates that the fault depression and depression have different characteristics of geothermal distribution (Fig.8). According to the data, a new geothermal gradient map, at different depth of 1000,2000,3000,4000 of XJWZ fault depression, is drawn (Fig.9).

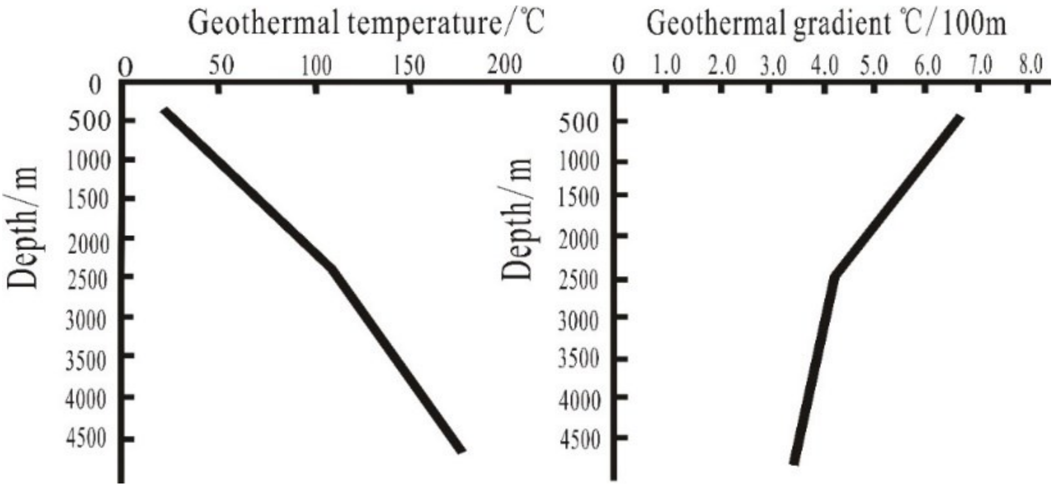


Figure 8: Relations map of the geothermal temperature, geothermal gradient with the depth.

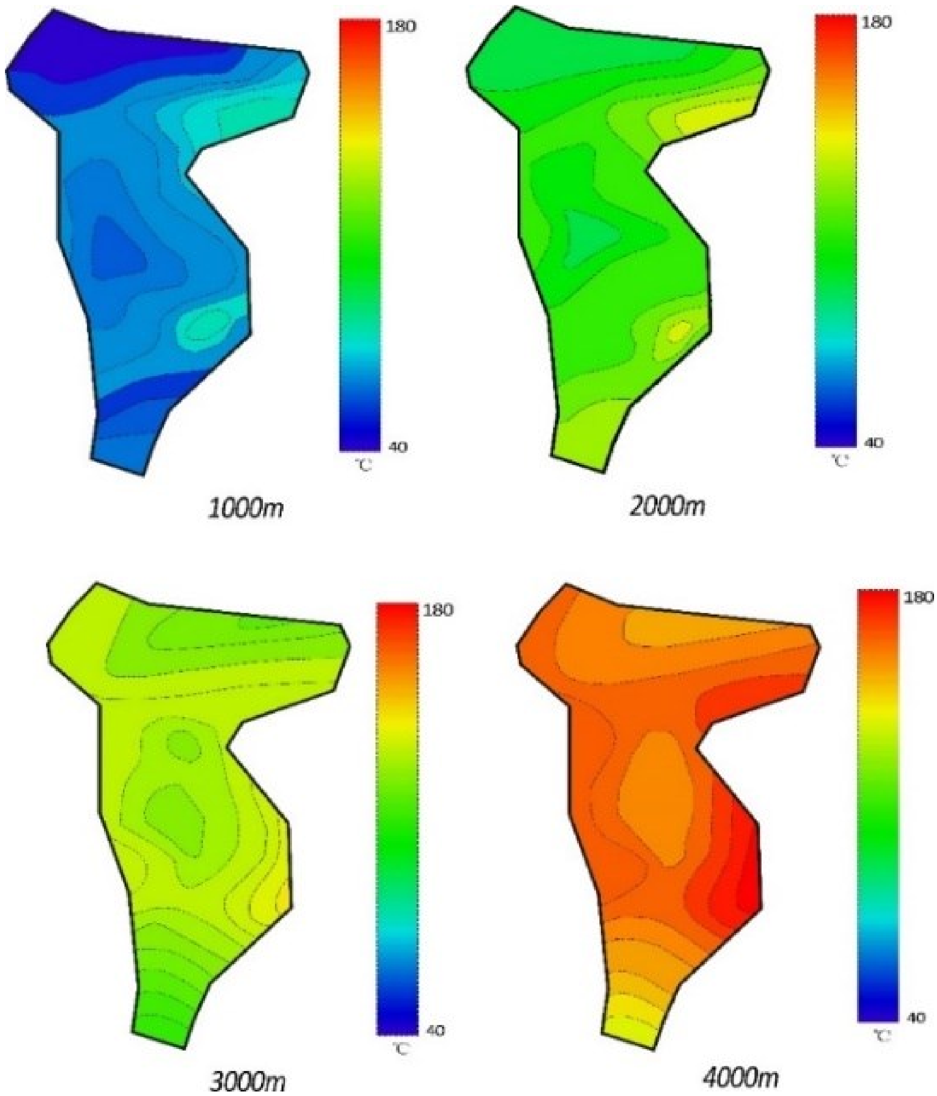


Figure 9: Temperature distribution at different depth of 1000,2000,3000,4000 in XJWZ.

(1) Temperature distribution at different depth

At 1000m, the temperature ranges from 39-60℃ and the average value is 48℃; At 2000m, the temperature ranges from 75-140℃ and the average value is 96℃; At 3000m, the temperature ranges from 108-136℃ and the average value is 121℃; At 4000m, the temperature ranges from 144-180℃ and the average value is 162℃. In conclusion, the overall XJWZ fault depression possesses a high geothermal, decreasing from Xushen well area to the outward. In addition, the volcanic rock is very development, which has a certain influence on the geothermal temperature distribution.

(2) The distribution of the geothermal gradient

The geothermal gradient of the XJWZ fault depression is 3.9-6.5℃/100 m, the average value is 4.8℃/100 m, which is higher than that of the whole Songliao Basin. The geothermal gradient has a tendency to reduce with the increase of the depth.

3.2.2 Rock thermal properties

Through the determination of the thermal conductivity of 11 rock samples in XJWZ fault depression (Table 2), we find that the thermal conductivity of magmatic rocks is generally higher than that of the sedimentary rock; All rocks' thermal conductivity was increased slightly with depth. The heat of the deep heat source was transferred from the rock with high thermal conductivity to the rock with low thermal conductivity, however, due to a low thermal conductivity of the rock above which has a poor heat conductivity, a relatively insulating cover is constituted, making the heat from lower part not lost. Therefore, the lower high thermal conductive layers have low geothermal gradient and upper layers have a higher geothermal gradient, namely the increase of geothermal gradient and the increase of thermal resistance of the rock are consistent, forming the geothermal gradient decreases with depth.

Table 2: Determination of the rock thermal conductivity in XJWZ fault depression

NO.	Depth (m)	Forma.	Lithology	Heat Conductivity (W • (m • K)$^{-1}$)			Anisotropy	Sample length (mm)
				Ave	Min	Max		
XS1	4231.8	K1sh	Mudstone	2.476	2.417	2.579	0.065	42.8
XS6	3850.7	K1yc	Rhyolite	3.103	2.987	3.212	0.073	31.2
XS21	3657.5	K1yc	Gritstone	2.766	2.662	2.869	0.075	57.1
XS21	3659.7	K1yc	Tuff	2.782	2.491	2.921	0.154	46.3
SX7	3730.8	K1yc	Tuff	2.829	2.563	3.305	0.262	54.4
SS3	3290.5	K1yc	Sandstone	2.393	2.261	2.557	0.124	42.8
SS3	3712.7	K1sh	Silty mudstone	2.4	2.249	2.572	0.135	54.4
ZS1	1755.9	K1qn	Siltstone	1.3	1.186	1.429	0.187	39.3
GS1	4489.9	K1yc	Tuff	3.353	3.183	3.511	0.098	41
WS904	2968.9	K1yc	Volcanic	2.769	2.504	3.117	0.221	59.8
S16	938.6	K1qn	Packsand	1.694	1.618	1.798	0.106	59.7

3.2.3 HDR resource evaluation

Use the volume method to evaluate the HDR geothermal resource.

$$\mathrm{Q} = \rho \cdot \mathrm{C}\rho \cdot \mathrm{V}(T - T_0) \quad (1)$$

where Q, ρ, V, Cρ, $\mathbf{T}$, $T_0$are heat quantity, density, volume, specific heat, temperature of the rock at certain depth, reference temperature, respectively.

The thermodynamics parameters of rocks are from the Daqing Oil field company. The total subsurface HDR geothermal energy in XJWZ is 2.73×10^{20}J from surface to a depth of 1 km, 7.44×10^{20}J from 1 km to 2 km, 1.18×10^{21}J from 2 km to 3 km, 1.56×10^{21}J from 3 km to 4 km.

4 RESERVOIR STUDIES (YINGCHENG FORMATION OF YS2 WELL)

We finally select the YS well area of east XJWZ to evaluate the feasibility of EGS development, because we have obtained rich data of three exploration wells YS1, YS2, YS4, such as geology, logging, well logging and fracturing in cooperation with the oil field company. Now, the three wells have been sealed due to the low gas production rate.

4.1 Deep hole data

The geophysics exploration results of the Yingshan-Shuangcheng depression, including the three wells. We choose the YS2 as the research well because the three wells are very close. Table 3 shows the basic data of the three wells. Because the Yingcheng formation range in 3784m-5020m and the corresponding temperature is 150℃-200℃, the Yingchen formation is the most probable target reservoir for HDR development.

Table 3: Basic data of YS1, YS2, YS4.

NO.	Depth (m)	Geotherma gradient (℃/km)	Bottom hole temperature (℃)	Potential reservoir		
				Denglouku Form.	Yingcheng Form.	Shahezi Form.
YS1	4739	40	175	2805.0~ 3613.0	3613.0~ 4619.5	4619.5~ 4800.0
YS2	5283	38	170	2972.5~ 3784.0	3784.0~ 5020.0	5020.0~ 5477.0
YS4	4850	38	180	2805.0~ 3892.0	3892.0~ 4475.0	4475.0~ 4650.0

4.2 Physical properties

Upper lithology is mainly glutenite, medium and lower lithology is mainly rhyolite, rhyolitic tuff, rhyolitic tuff lava and andesitic basalt. Latest isotope test data confirmed that the volcanic rocks of Yingcheng group is mainly formed in about 102-107Ma. The volcanic reservoir in Yingcheng group has little water, which is ancient sedimentary water; it has a dense lithology (permeability is 0.001-0.1mD), small porosity (0-12%) and very thick rock. The reservoir contains rich natural fracture, the image statistical results show that the reservoir face rate is generally 1%-3%, pore width less than 0.2 mm, micro-pore and micro-crack are rich.

4.3 Reservoir stimulation

4.3.1 Hydraulic fracturing history

In order to extract natural gas, the Daqing oil company have conducted test fracturing and gel-proppant fracturing in 173Ⅲ layer (3879m-3900m) in YS2 well, 2008. Fracture parameters are shown in Table 4. The in-situ stress gradient is 0.0246 MPa/m. Fig. 10 shows the interpretation results of in-situ stress (An MY et al., 2002).

Table 4: Reservoir parameters for fracturing simulation.

Perforated interval (m)	Pore (%)	Per (md)	Den (g/cm3)	Compressive strength (MPa)	Young modulu (GPa)	Poisson's ratio	Fracture toughness (MPa·$m^{0.5}$)	T (℃)
3879.52-3900.27	9.4	0.597	2.49	677.01	50.46	0.209	1.682	153

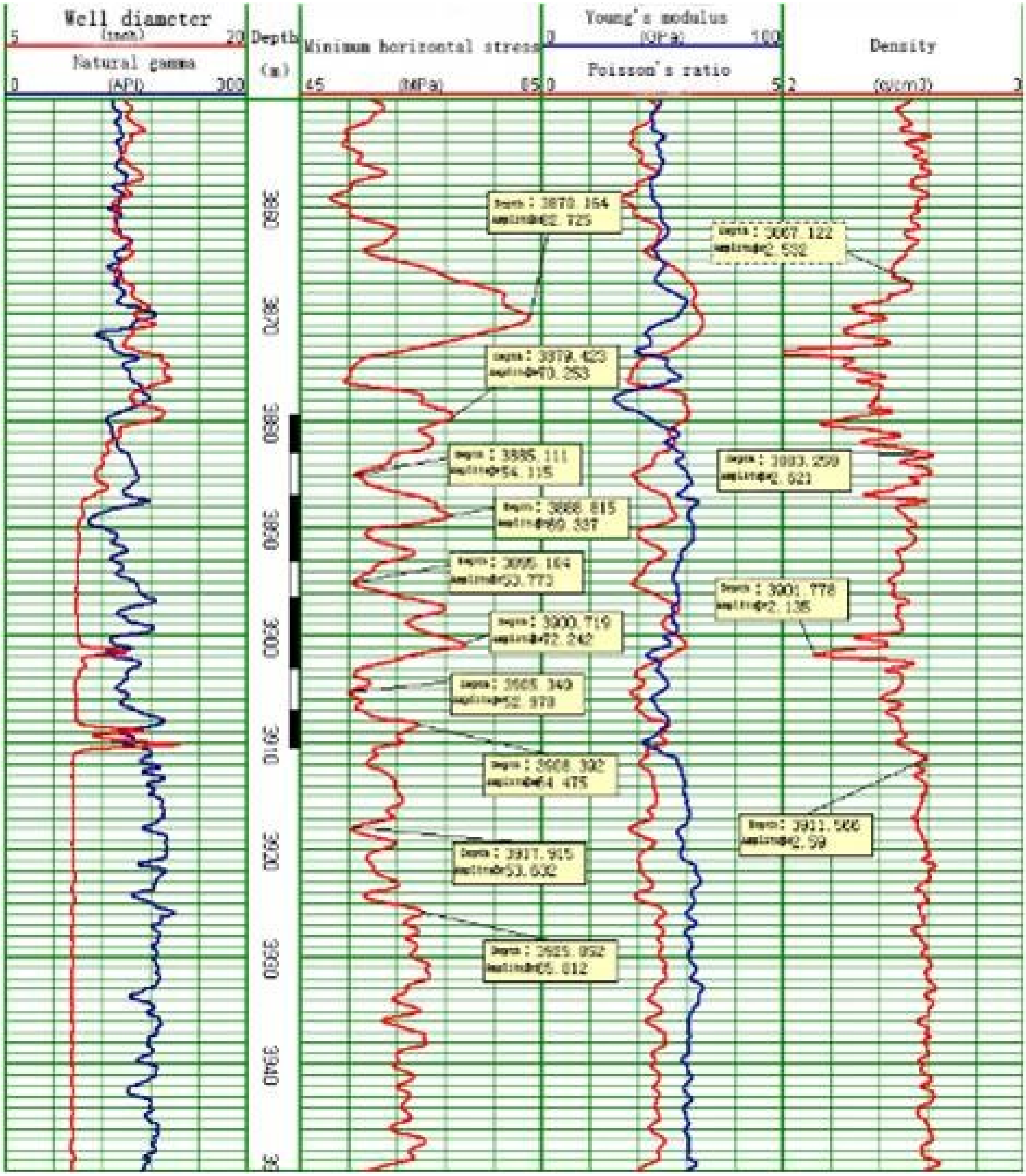


Figure 10: In-situ stress interpretation results of 173Ⅲ layer, YS2 well..

Test fracturing operations were conducted to confirm the formation property and select the targeted measures and operation parameters .The results of the test fracturing are shown in Table 5.

Table 5: Parameters for test fracturing operation and interpretation results

Time (min)	Pressure (MPa)	Interpretation results	
0	44.9	Items	Results
5	42.9	Leak off coefficient (×10-4μm2)	0.8
10	42.11	Filtration Multiple	0.2
15	41.4	Fracturing fluid efficiency (%)	74.5
20	40.7	Number of Micro fracture	3
25	40.1	Fracture aperture	0.2
30	39.6	Net pressure (MPa)	7.67
35	39.1	Friction of fracture (MPa)	7.9
40	38.6	Closure pressure (MPa)	75.61
45	38.1	Closure time min	48.47
50	37.7	Pump stopping pressure gradient (MPa/m)	0.0215

The interpretation results for the test fracturing operation show that the operation pressure is high. The micro fracture is well developed. The friction of fracture is large, and the pump stopping pressure gradient is high.

4.3.2 Numerical simulation

Numerical simulation code and basic assumptions

A simplified geologic model of the field is established to simulate the hot water production of the geothermal field. Simulation was conducted by the advanced simulator TOUGH2 developed by Lawrence Berkeley National Laboratory (Pruess, 1999). To ensure computational efficiency, the following assumptions were made.

1. Water loss will not occur during the injection and production. Actually, the volume of water loss may exceed 30% according to the fluid efficiency of test fracturing. When the circulation time is long enough, we assume the wall rock reach saturation. The deviation caused by ignoring the water loss is acceptable to a certain extent.

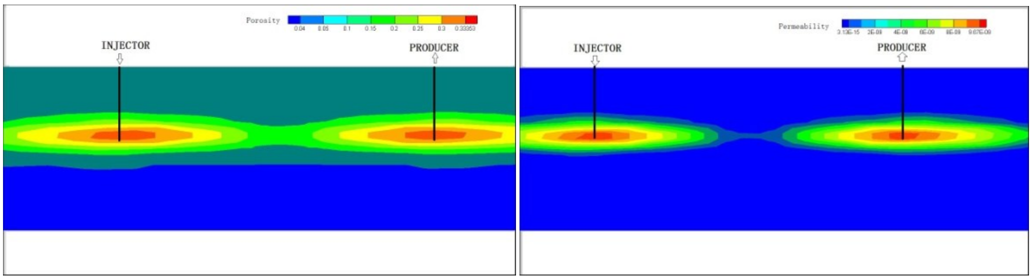
2. The coupling effects of fluid mechanical, chemical, and thermal processes are neglected in this study. McDermott et al. found that the heat production power is at minimum when the water properties serve as the functions of temperature, pressure, and salinity. By contrast, the rock properties are constant without considering the mechanical interaction between rock and fluid as well as the rock thermo-elastic effect (McDermott CI et al., 2006). Based on these conditions, the heat production when rock keeps constant physical property can be considered as the lower limit of system thermal output (Yu-Chao Zeng et al., 2013).

3. In order to reduce the upfront costs as much as possible, the well design pattern of two vertical wells is chosen using abandoned oil wells.

Geometry, domain discretization, initial conditions and properties

Layers between 3,800 m and 4100 m were chosen as the simulation zone in this study. Areas beyond the simulation zone are treated as the cap and base rocks, which are not involved in the calculation. The simulation zone consists of three different layers in the vertical direction, an upper layer, a bottom layer and a reservoir layer. The reservoir layer has relatively high permeability comparing with the other two layers. The size of the model in this study is 7,850 m*1,943 m*300 m, meshed into 10,500 grids. The fractured crack is nearly vertical in the formation. The two wells are located at a horizontal distance of nearly 600 m from each other and penetrate into the depth of 3,930 m.

The initial thermal and pore pressure conditions are established through graded assignment. The initial temperature of the reservoir is approximately 155 °C at a depth of 3,800 m, which gradually increases to 167 °C at a depth of 4,100 m. Pore pressure increases from 38 MPa up to 41 MPa correspondingly.Units with fracture property are established at specified areas to simulate the stimulation effects on the reservoir. The length of the fracture is 600m, the height is 300m, aperture is 0.006m, which are assigned to the corresponding units through a FORTRAN code (Fig.11).



(a) **(b)**

Figure 11: The distribution map of the porosity (a) and permeability (b) in the fracture layer nearby the injection well and production well.

Table 6 presents the main parameters for the simulation. The fracture zones are divided into three secondary units, and the values of the permeability and porosity are distributed in the form of oval zone. The conductivity of the fracture decreased by gradient with the increase of the distance to the stimulation position based on this feature.

Table 6: Main parameters for hydro-thermal coupling simulation.

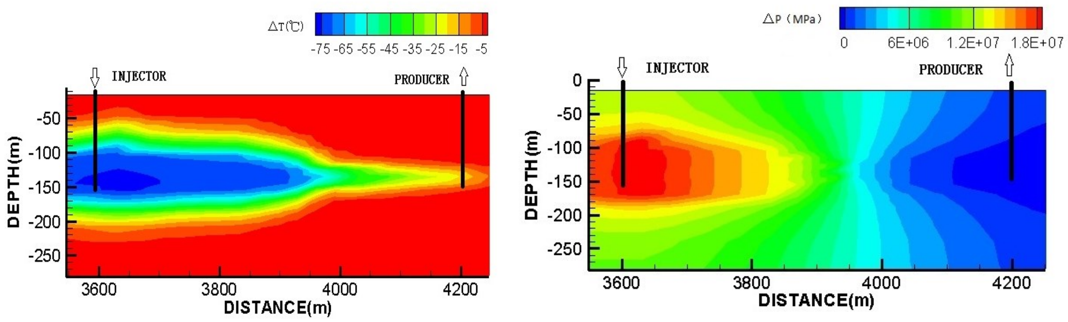
Items	Cap rock	Reservoir	Base rock	Frac Zone1	Frac Zone2	Frac Zone3
Porosity	0.06	0.083	0.042	0.137	0.275	0.412
Permeability	$1*10^{-16}$	$3.2*10^{-16}$	$0.8*10^{-16}$	$0.34*10^{-10}$	$1.68*10^{-10}$	$3.35*10^{-10}$
Specific heat	1000	1000	1000	1000	1000	1000
Thermal cond	2.5	2.5	2.5	2.5	2.5	2.5

Simulation scenarios

Three different working conditions are simulated on the same model to predict the hydrothermal production of the reservoir after stimulation. The injection rates of the three working conditions are 5, 10, and 15 kg/s. The corresponding theory production rates are 4.6, 9.2, and 13.8 kg/s, respectively. The injection temperature of the three simulation scenarios are all 87 °C.

Analysis of simulation

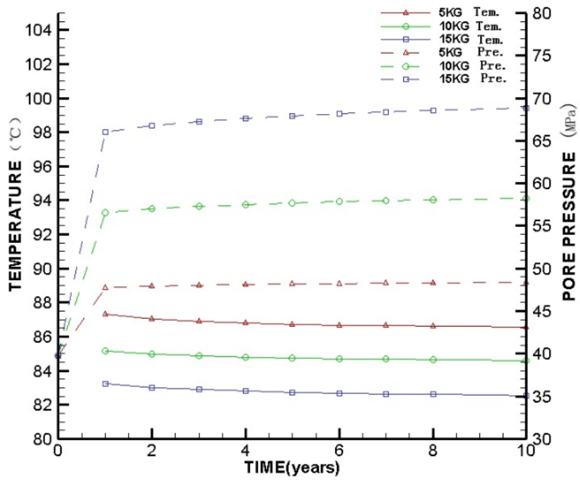
During the 10 years of simulation, the maximum increment of pore pressure appeared in the first year. Afterward, the growth rate decreased and stabilized after 10 years of injection and production. Unlike the feature of the change of pore pressure, the temperature dropped approximately the same quantity each year and did not stabilize after 10 years of simulation. Fig.12 shows the calculated changes in temperature and pore pressure under the injection rate of 10 kg/s after 10 years of injection and production. The simulation results indicate that the temperature near the injection well decreased to 13.9 °C, and pore pressure near the production well increased to 18.9 MPa.

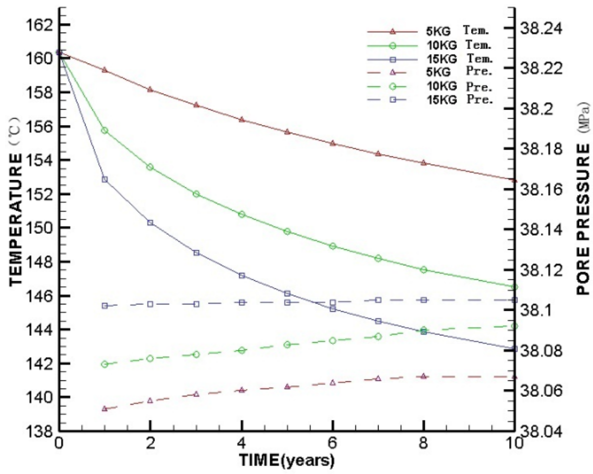


(a) **(b)**

Figure 12: Calculated changes in temperature (a) and pore pressure (b) under the injection rate of 10KG/S after 10 years of injection and production.

Figure 13 indicates that the pore pressure near the injection well increased as the injection rate increased, whereas the temperature near the production decreased. After 10 years of simulation, the pore pressure increased to 9.2 and 29.2 MPa at the injection rates of 5 and 15 kg/s, respectively, and temperature lowered to 7.5 °C and 17.5 °C, respectively.





(b) **(b)**

Figure 13: Calculated changes of temperature and pore pressure versus time nearby the injection well (a) and production well (b).

Evaluation of EGS development potential in XJWZ

Through the temporal and spatial distribution of temperature and pore pressure under different injection rates, the temperature dropped to 7.5 °C after 10 years of simulation at the injection rate of 5 kg/s. This finding illustrates that the hydrothermal production can be further improved. When the injection rate is 15 kg/s, the temperature decreased to 3.6 °C compared with the injection rate of 10 kg/s near the production well. Pore pressure increased more than 10 MPa. The significant increase of pore pressure illustrates that the injection rate of 15 kg/s exceeded the limit of the conductivity of the fracture. When the injection rate is 10 kg/s, the temperature dropped to 13.9 °C after 10 years of simulation. The value of the temperature reduction is within a reasonable range.

Based on the flow rate (10 kg/s) and resources temperature (150 °C), its electricity generating capacity is nearly 1.5 MWe.

Methods for improving hydrothermal production

The improvement of stimulation techniques is a reasonable way of promoting hydrothermal production. In addition, using two horizontal wells with network fracturing will enhance the hydro-rock heat exchange areas to improve the injection volume and slow down the diffusion rate of low-temperature regions.

5 CONCLUSIONS

This study introduced the first possible EGS site in China (i.e., Xujiaweizi pilot) from several aspects, such as geographical position, geological structure, temperature characterization, porosity and permeability of the reservoir, and fluid characteristics. Through the hydrothermal simulation, a first-stage evaluation of EGS development potential in XJWZ was conducted. Methods for improving hydrothermal production were proposed. The following conclusions were made based on the results.

1. The XJWZ is located in northern Songliao Basin, which is one of the areas in China with the highest geothermal potential. The geothermal geology condition is favorable for geothermal generation. Several oil–gas wells are located in this area. Songliao Basin has huge advantages for developing HDR resources in consideration of various factors such as mineable reserves, temperature conditions and mining costs.

2 .The hydrothermal production of XJWZ is nearly 10 kg/s based on the fracturing method used in this study. The electricity-generating capacity is approximately 1.0 MWe to 1.5 MWe. The hydrothermal production of the XJWZ is considerably less than that needed for commercial operation. However, the XJWZ is sufficient to be built as a demonstration site for scientific research on EGS.

3. Improving stimulation techniques is a reasonable way to promote hydrothermal production.

The results of the analyses described above indicate that while there will be many problems needed to be considered, the XJWZ area has the potential for EGS development.

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