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Large Karstic Geothermal Reservoirs in Sedimentary Basins in China: Genesis, Energy Potential and Optimal Exploitation

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ABSTRACT

Carboniferous rock formations are widely found in sedimentary basins in China. Geothermal reservoirs are formed in these rock formations. A major part of the hot water used for space heating in north China is abstracted from these formations. In order to properly assess the energy potential of these reservoirs and to work out a rational mode of exploitation, systematic research has been carried out in the last a few years, taking several fields in the Bohaibay Basin as examples. Based on heat flow measurements, geotemperature field measurements and modeling, coupled with groundwater circulation studies, it has been found out that the heat accumulation in the upper crust is realized by two coupled processes: one is the heat re-distribution by differentiated heat flux due to difference in thermal conductivity of the formation rocks, the other is the heat sweep effect of basin-scale regional groundwater circulation. Water temperature is the highest if the two processes are both enhanced by tectonic conditions. Injection tests of waste water have been performed to define an optimal mode of exploitation. Karstic reservoirs are fund easy to inject, when gravity injection is concerned, one injection well can accommodate waste water from two production wells, which is a major advantage over sandstone reservoirs in the same region. Actual injection can be optimized based on tracer tests. Numerical experiments have shown that, life time of a field can be further elongated if injection is placed outside of the field with reasonable distances from the main production zones. Hot water in the karstic reservoirs in Xiongxian County of Hebei Province has been efficiently utilized to a large scale for space heating. Similar practice can be reproduced in other regions of the country. Similar karstic reservoirs are found to exist in several big sedimentary basins in China, so the energy potential is huge if developed.

1. INTRODUCTION

Karstic geothermal reservoir is a type of geothermal resources mainly referring to limestone, dolomite and other soluble rocks as the main geothermal energy storage medium. A major part of the hot water is abstracted from these formations. The total area of carbonate rocks in China is more than one-third of its land area. Among them, the outcrop area is 9×10^5 km^2, buried area is more than 2.5×10^6 km^2 (Pang et al., 2012). Many sedimentary basins developed over the craton basement of North China have good geological conditions to develop deep karstic geothermal reservoir resources, such as Bohaibay Basin, Yangtze Basin, and Tarim Basin.

Through interpretation the genetic mechanism of Xiongxian district of Niutuozhen geothermal field in North China Basin, and Cangxian uplift in Bohaibay Basin, this article presents that the heat accumulation in the shallow crust of sedimentary basins in China has been realized by a two precesses: one is the heat re-distribution by differentiated heat flux due to difference in thermal conductivity of the formation rocks, the other is the heat swipt effect of regional groundwater circulation. Hot water temperature is the highest if the two processes are both enhanced by tectonic conditions.

Assuming 15% recovery, the geothermal energy storage of karstic reservoirs in the sedimentary basin is about 344 billion tons of standard coal equivalent, which shows a very high potential for space heating, replacing coal. And the exploitation of karstic reservoir geothermal resources is at an early stage at present in China. In addition, the exploitation modes that dispersed exploitation-injection mode and peripheral concentrated exploitation-injection mode were analyzed for karstic geothermal reservoir of sedimentary basins in China.

2. GENETIC MODEL OF KARSTIC RESERVOIR GEOTHERMAL RESOURCES IN SEDIMENTARY BASIN

The sedimentary basins in mainland China include rift basin (such as Songliao basin, Bohai bay basin and Junggar basin of late Paleozoic era), depression basin (such as Ordos basin), and foreland basin (such as the Kuqa depression of Tarim basin and southern margin of Junggar basin). Their geothermal condition are controlled by the tectonic environment, due to the difference of development and evolution of the basin tectonic environment, the geothermal distribution, thermal evolution, deep lithosphere hot structure are obvious different(Qiu et al., 2004).

Geothermal resources in the hot and warm basins in northern China are fed by elevated heat flux from mantle upwelling in a rifting tectonic background, the Bohaibay Basin is a typical example.

2.1 Niutuozhen uplift geothermal field

Niutuozhen geothermal field located in Northern China sedimentary basin (Figure 1) is formed under the normal heat background, basal bump is the main reason for the formation mechanism of heat. The average heat flow is 75.69 mW/m^2 in Niutuozhen geothermal field, while the value of heat flow is 50.24 mW/m^2 for Langfang-cpmpany sag and 41.87 mW/m^2 for Baxian sag. The heat flow of bump is significantly greater than the concave area which illustrates the basal's thermal control effect.

The Xiongxian geothermal region is typical belong to conduction type, the geothermal temperature increase in a linear with the increase of the depth. Upper cover has high geothermal gradient, and the average geothermal gradient is 5.1℃/100m; lower reservoir has the average geothermal gradient of 0.62℃/100m (Han, 2010), which shows the typical karstic geothermal reservoir's characteristics.

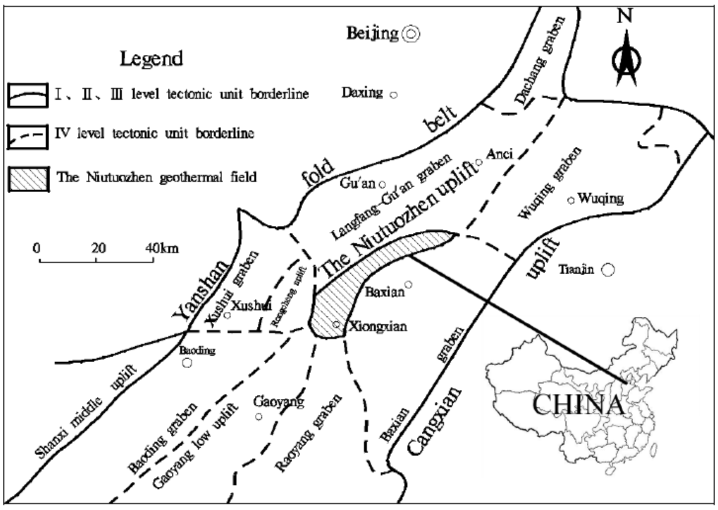

Figure 1: Location of Niutuozhen geothermal field and Cangxian uplift in regional tectonics in Northern China (from Wang, 2009)

2.2 Cangxian uplift

Cangxian uplift is located in the active belt of East Asia continental margin, is belongs to a large rift sedimentary basin. Wumishan group in Jixian system is the most important reservoir layer due to its high fluid temperature in Tianjin region, and carbonate rock is the main lithology for the Wumishan group (Duan, 2007).

According to hydrological geology and geothermal heat reservoir geological data, the hydrogeological conceptual model of the geothermal reservoir shows that thermal reservoir temperature exposed by Wumishan group is affected by the circulated depth of reservoir fluid, and reservoir permeability is controlled by structure and fracture. It would be summarized (1) thermal reservoir's temperature is higher when the geothermal reservoir is located on a convex structure; (2) thermal reservoir's temperature is higher when the geothermal reservoir is located on tectonic fault well developed region due to big circulation depth of reservoir fluid.

The heat accumulation in the karstic geothermal reservoir in Bohai bay basin has been realized by a two processes: one is the heat re-distribution by differentiated heat flux due to difference in thermal conductivity of the formation rocks, the other is the heat swipt effect of regional groundwater circulation. That is basement uplift, deep fracture and new tectonic fault are main structure premise for geothermal resource formation in sedimentary basin, and fault cutting geothermal reservoir is a good channel for deep heat fluid and groundwater circulation.

3. ENERGY POTENTIAL OF KARSTIC GEOTHERMAL RESERVOIRS IN SEDIMENTARY BASINS

Karstic geothermal reservoirs are widely found in bedrock of sedimentary basins in northern China. Owing to the heat partitioning as a result of difference in thermal conductivity between sand and limestone, coupled by heat accumulation caused by regional groundwater circulation, there exist rich geothermal resources in the buried karstic formations. The sedimentary basin where it is located is rich in karstic geothermal resources. This is typically a coupled process between high thermal background resulting from Craton destruction and heat accumulation brought by regional groundwater circulation in the carbonate formations.

The karstic geothermal reservoirs are characterized by high single well yield, low water salinity, easy extraction and injection, high load factor, less environmental impact. They have the potential to be exploited on a large scale (Pang et al, 2012).

Xiongxian County of Niutuozhen geothermal field, Hebei Province has utilized karstic geothermal reservoirs for space heating, setting up a successful example for others. Using an analogue approach, we have estimated the karstic geothermal resources in China to be more than 344 billion tons of standard coal equivalents, assuming 15% recovery, which shows a very high potential for space heating, replacing coal. It is anticipated to contribute considerably to climate change and air pollution mitigation in northern China.

Geothermal resources evaluation method mainly include plane crack method, the surface heat flux method, magma heat balance method, volumetric method, analogy method, and the geothermal reservoir simulation method, etc.

Volumetric method is also called the thermal storage method, which can be used to calculate the total heat storage in rock mass and fluid. Formula adopted by the method is based on a set of geological and physical parameters, which could be given accurately for a particular study area, and the method is similar with oil and mineral resources assessment. The volume method is being used in geothermal resources assessment widely. Analogy method is one of the volume method, it use the parameter value of area besides a set of fixed parameters which are same as the volumetric method.

3.1 Volumetric method to calculate geothermal resources in karstic reserviors

The volumetric method is not only applicable to porous geothermal reservoirs, but also to fractured geothermal reservoirs. The parameters' value of specific heat, density and porosity for rocks and fluids could be accurately obtained in the laboratory. The actual equations of volumetric method are:

$$Q = V\,(T - T_0)\left[\rho_r c_r (1 - \Phi) + \rho_w c_w \Phi\right] \quad (1)$$

$$Q_{Re} = Q R_E \quad (2)$$

$$Q_w = V\Phi \quad (3)$$

$$Q_{RE} = V\,(T - T_0)\,\rho_w c_w \Phi \quad (4)$$

Where Q: the heat contained in geothermal reservoir (KJ); Q_W: hot fluid stored in geothermal reservoir (KJ); Q_{Re}: Heat can be recycled which could be exploited out from total heat resource (K)); R_E: recovery rate (%); V: geothermal reservoir volume (m3); ρ_r: density of rock, kg/m^3; $\rho_{w:}$ density of water, kg/m^3; T: the average temperature of the rock and water in the specified volume (℃); T_0: reference temperature (^{o}C); C_r: heat capacity of rock, J/(kg·°C); C_w: heat capacity of water, J/(kg·°C); Φ: porosity of permeability layer.

The total heat energy stored in tertiary sandstone geothermal reservoir and carbonate rock geothermal reservoir in the Xiongxian geothermal region amount is 35.8±8.3×1016 kJ, convert into standard coal of 122.4±28.5 billion tons.

Consider recovery rate is 15%, recyclable heat was 7.5±1.8×1016 kJ, convert into standard coal of 25.6±6.1 billion tons. The volume of hot water is 2849.7±289.7 billion m^3. The heat contained in hot water is 12.2±3.4 kJ, convert into standard coal of 41.6±11.6 billion tons.

3.2 The geothermal resource assessment using analogy method

Using an analogue approach, we have estimated the karstic geothermal resources in China to be more than 344 billion tons of standard coal equivalent (Table 1), assuming 25% recovery, which shows a very high potential for space heating, replacing coal. It is anticipated to contribute considerably to climate change and air pollution mitigation in China.

Table 1: The calculated results of geothermal resource in sedimentary basin using analogy method

Geothermal reservoir characteristics	Xiongxian region	Sedimentary basins in China
Buried hill area (km^2)	307	225000
Buried hill area/basin area	0.09	0.09
Thickness of buried hill (m)	3600	3600
Geothermal resource (10^{18} KJ)	0.145	106
Recoverable standard coal (10^8 t)	12	9088
Recoverable hot water (10^8 m^3)	314.5	230497
Standard coal (10^8 m^3)	4.7	3445

4. EXPLOITATION MODE OF KARSTIC GEOTHERMAL RESERVOIR IN SEDIMENTARY BASINS

Water recharge to geothermal reservoirs is slow. The unreasonable planning and overexploitation could cause damage to geothermal reserviors, and a series of environmental pollution and geological hazards.

According to the distribution of injection wells, exploitation mode of geothermal resource would be divided into two types: one is dispersed exploitation-injection mode, which exploited well and injection well are interphase distributed. This mode could save project cost, and supply geothermal reservoir pressure timely, and the disadvantage is that may cause thermal cooling in short time.

The other is peripheral concentrated exploitation-injection mode, which the exploitation wells are arranged in the production region and injection wells are arranged in the injection region. Those two regions are independent relatively and there is a certain distance between them. The advantage of this mode is that it could reduce the risk of geothermal temperature cooling. But the disadvantage is that it couldn't recharge geothermal reservoir pressure quickly, and cause great temperature drop in the focus injection region.

In order to establish the most scientific sustainable development and utilization mode of geothermal resources, choosing same layer or different layer to inject the heat-extracted water should be considered also.

Reinjection experiments are necessary when large scale geothermal reinjection projects are being planned. In the Xiongxian geothermal system, karst fissures are well developed but their distribution is not uniform. On the basis of geothermal reinjection experiments carried out in this area the recharge capacity can be estimated, the likely hydraulic connections and flow channels studied and the impact of reinjection for the thermal reservoir system determined.

As Nituozhen geothermal field as an example, during the period of 2004-2010, the descending speed of underground water level up to 8 m/a, has a observably impact on the development of geothermal water for the long time. The paper established numerical model of Niutuozhen geothermal field according to the dispersed exploitation-injection mode and peripheral concentrated exploitation-injection mode, to predict the evolution of pressure and temperature of geothermal field based on practical production and injection scene. There we present to model simulation results to analysis the effect of the two exploitation-injection modes.

For dispersed exploitation-injection mode, temperature drop appear around reinjection wells, the drop range is 1-2 ^{o}C or 10 ^{o}C for some extremely wells (Figure 3). For concentrated production and reinjection mode, temperature drop appear mainly focus reinjection region (Figure 5), which couldn't influence the exploitation in production area much. The pressure of reservoir system remains unchanged almost after exploitation-reinjection get balance (Figure 2 and Figure 4).

The distance between an injection well and a production well should be considered strictly when adopting dispersed exploitation-injection mode, especially in a narrow region. For peripheral concentrated exploitation-injection mode, geothermal reservoir temperature drop area mainly concentrated in the injection region. From the maintainable and sustainable development of geothermal field aspect, peripheral concentrated exploitation-injection mode is better than dispersed exploitation-injection mode for karstic geothermal reservoir in sedimentary basins.

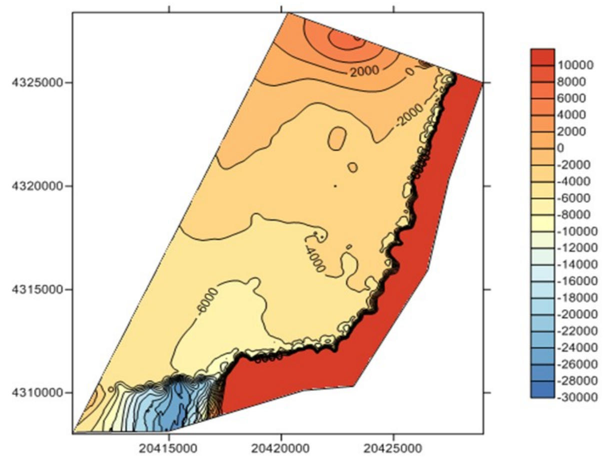

Figure 2: Pressure field after 10 years with in-field exploitation-injection mode

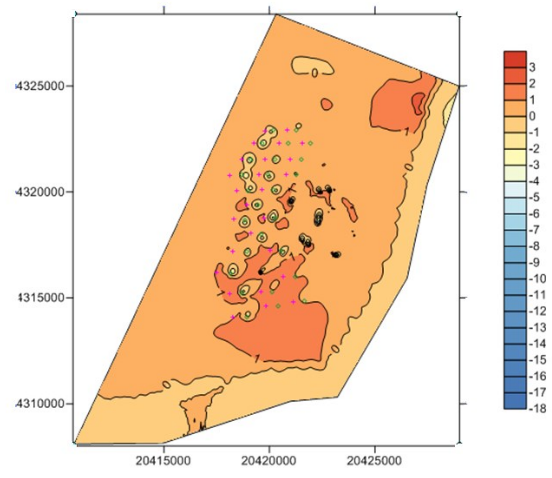

Figure3: Temperature field after 10 years with in-field exploitation-injection mode

5. CONCLUSIONS

1) The heat accumulation mechanism in the karstic geothermal reservoir in Bohaibay Basin is realized by two coupled processes: one is the heat re-distribution by differentiated heat flux due to difference in thermal conductivity of the formation rocks, with that of the karstic rock about three times higher than that of the sandstone formation; the other is the heat sweep effect of regional groundwater circulation at the basin scale.

2) Xiongxian sector of the Niutuozhen geothermal field has been developed successfully to provide space heating for the city at large scale. Using an analogue approach, estimated karstic geothermal resources in China amount to more than 344 billion tons of standard coal equivalent, assuming 15% recovery, which is very promising for space heating in northern China, replacing coal, and contributing to reduction of greenhouse gas emission.

3) Numerical modeling results show that, as far as sustainable development of geothermal field is concerned, peripheral concentrated injection mode is better than current dispersed exploitation-injection mode for karstic geothermal reservoirs in sedimentary basins.

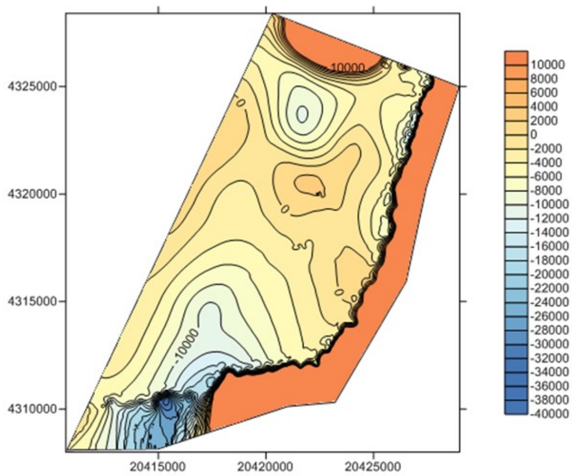

Figure4: Pressure field after 10 years of production with peripheral concentrated injection mode

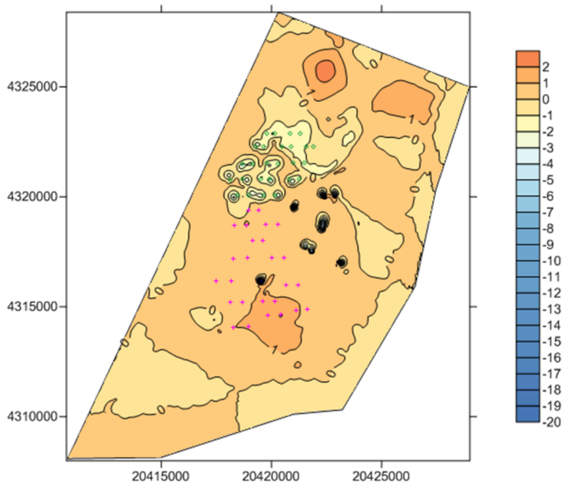

Figure 5: Temperature field after 10 years of production with peripheral concentrated injection mode

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