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Combined Monte Carlo Simulation and Geological Modeling for Geothermal Resource Assessment: a Case Study of the Xiongxian Geothermal Field, China

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ABSTRACT

Potential assessment is a consistent work through all stages of geothermal resource development. Several methods have been developed which depends on the availability of reservoir data. The volume method is preferred and has been widely used in the early phases of geothermal development. As data are limited and have high uncertainty at early stages of geothermal development, stochastic and risk analysis methods such as Monte Carol simulation are frequently used to estimate the range and probable distribution of stored heat reserves. However, it is usually difficult to determine the temperature and volume of the reservoir, especially when the geological structures are complicated. Here, we propose a combined method based on Monte Carlo simulation and geological modeling to characterize both the uncertainty of the temperature and volume of the reservoir, supposing both have a triangle distribution. The geological solids of both the reservoirs and caprock are constructed using Gemcom surpac, and the characteristic values of the reservoir temperature and volume are calculated. Taken the Xiongxian Geothermal Field of China as a study case, the stored heat energy of the Tertiary sandstone reservoir and the underlying Precambrian dolomite reservoir are calculated to be 7.28±2.16G TCE (1σ) and 4.96±1.86G TCE (1σ), respectively.

1. INTRODUCTION

Potential assessment is a constant work through all stages of geothermal resource development. Several methods have been developed which depends on the availability of reservoir data, such as geological structure, hydrogeological condition, geo-temperature field distribution, reservoir response to utilization, etc. Thus different methods are applied at different stages of the development. The volume method is preferred, and has been widely used, in the early phases of geothermal development which applies to both porous and fractured reservoirs. The recoverable heat is estimated from the thermal energy available in a reservoir using a thermal recovery factor, R_E, for the producible fraction of a reservoir's thermal energy calculated according to parameters of both reservoir rock and fluids, including rock density, porosity, temperature, reference temperature and volume, and fluids specific heat capacity. The thermal energy is calculated as

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

or

$$Q = AD\left(T - T_0\right)\left[\rho_r c_r\left(1-\Phi\right) + \rho_w c_w \Phi\right] \tag{2}$$

where Q is the stored heat, V is the reservoir volume, A is the area of the geothermal field, D is the reservoir thickness, T is the characteristic reservoir temperature, T_0 is a reference temperature, ρ_r and ρ_w are the rock and water density, respectively, c_r and c_w are the rock and water specific heat capacity, respectively, and Φ is the reservoir porosity.

The thermal energy that can be extracted at the wellhead is given by

$$Q_{Re} = Q R_E \tag{3}$$

where Q_{Re} is the recoverable heat energy, and R_E is the recovery factor.

In fact, the parameters in the volume method are not constant and usually they vary with some uncertainty. This is specially the case at early stages of geothermal development when data are limited. Thus stochastic and risk analysis methods such as Monte Carlo simulation are frequently used to estimate the range and probable distribution of the stored heat reserves. However, it is usually difficult to determine the temperature and volume of the reservoir, especially when the geological structures are complicated. Here, we propose a combined method based on Monte Carlo simulation and geological modeling (MCGM) to characterize both the uncertainty of the temperature and volume of the reservoir.

2. METHODOLOGY

The Monte Carlo method is a numerical statistical simulation method proposed in the middle of the 20th century (Metropolis and Ulam, 1949), where statistical simulation is defined in general as any method that utilizes sequences of random numbers to perform a simulation. In the method, the physical system is described by probability density functions (pdfs). Firstly, a probabilistic model describing a physical system is constructed, making the parameters equal to the solution of the problem. Then, random sampling is

conducted following the pdfs and characteristic statistical values of the parameters are calculated. Finally, the approximate solutions are given with the statistical error (the variance).

The essential component of a Monte Carlo simulation is the modeling of physical processes by one or more pdfs. Processes are defined as pdfs by using experimental data or theoretical models that describe their physics; then, one can sample an outcome from the pdf, thus simulating the actual physical process. While applying these pdfs, some statistical terms such as mean, variance, etc. are utilized. For each uncertain variable, one may define the possible values with a probability distribution which can be selected based on the conditions surrounding that variable. The common distribution types are normal, lognormal and triangular distributions. These input variables are then used in Monte Carlo simulations to define the stored and recoverable heat energy of the reservoir along with the associated uncertainties.

In the volume method, the calculated uncertainty of the stored heat (*Q)* is the result of the uncertainty related to the reservoir volume (*V*) and temperature (*T*), reference temperature (*T0*), rock porosity (Φ), the rock (*ρr*) and water (*ρw*) density, and rock (*cr*) and water (*cw*) specific heat capacity. Except for the reference temperature *T0* that can be estimated from the average annual atmospheric temperatures, these parameters are gathered through geological, geophysical, geochemical surveys or well logging. In order to characterize these uncertainties, we suppose that the parameters in the volume method have a triangular distribution, which is defined by three characteristic values, i.e., minimum, mode (here, we use the mean value instead) and maximum values (Fig. 1). Taken the reservoir temperature as an example, in Figure 1, t1, t3 and t2 are the lowest, highest and most probable temperature of the geothermal reservoir, respectively; while $\bar{t}$ is the mean temperature and σ_t is the standard deviation. Thus the black area between *t* and *t*+⊿*t* donates the probability of the reservoir temperature to fall in the range of t to t+⊿t. The three characteristic values of each parameter are determined as follows.

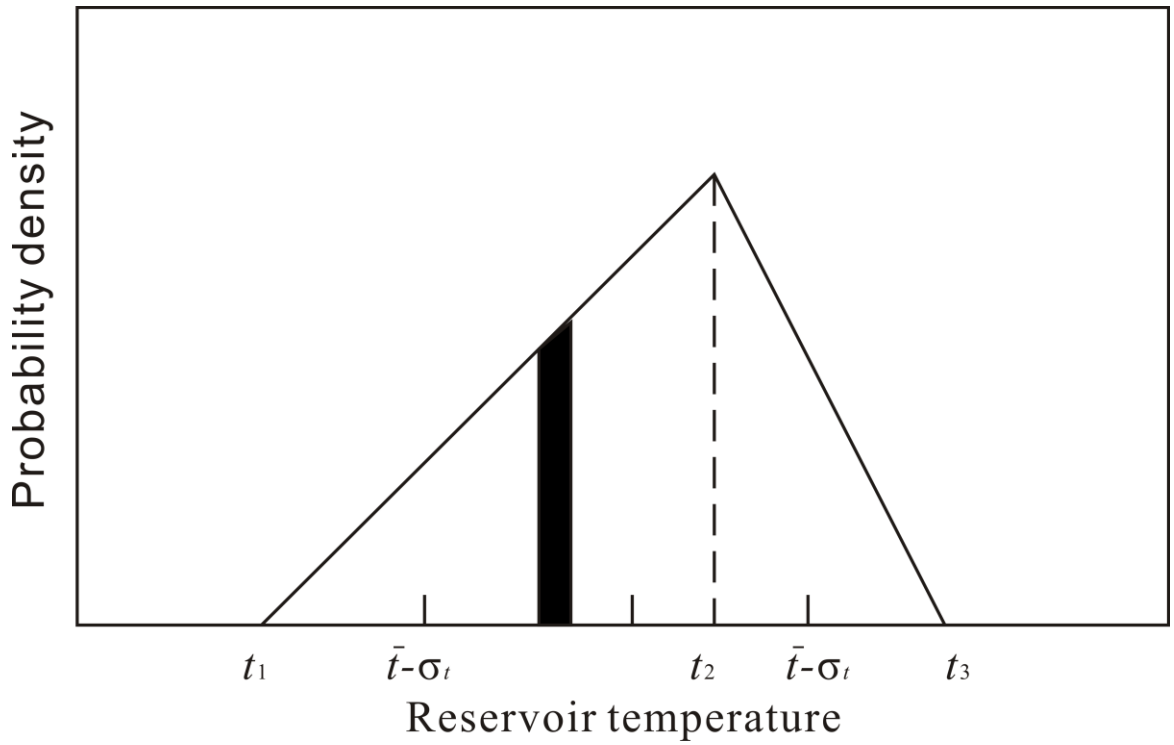

Fig.1 Triangular distribution of reservoir temperature

2.1. Reservoir volume

According to the Assessment Method of Geothermal Resources (DZ40–85), 40℃ is regarded as the lower temperature limit for geothermal resources of low to medium temperature. Thus only the groundwater with temperature above 40℃ is considered in the assessment, i.e., the reservoir volume is the rock volume between the bedrock and the caprock when the 40℃ isothermal surface is located above the caprock, and it is the rock volume between the bedrock and the 40 ℃ isothermal surface when the 40℃ isothermal surface locates below the caprock. Here, we calculate the characteristic values of the reservoir volume though 3D geological modeling, using the geology and mine planning software Gemcom Surpac. The geologic solids of both the reservoirs and caprocks are built firstly, based on the geological data of the geothermal field, and the "40 ℃ isothermal surface" (it is actually a plane for calculating the reservoir volume where the groundwater is above 40 ℃ by interception with the reservoir solid) for each reservoir is calculated. Then, the reservoir volume with groundwater temperature above 40 ℃ is calculated though DTM (Digital Terrain Models) calculations using the "Solids tools". The maximum, minimum and mean burial depth of the "40℃ isothermal surface" can be determined by the maximum, minimum and mean geothermal gradient of the caprock and reservoirs, and accordingly the minimum, maximum and mean reservoir volumes are obtained.

2.2 Reservoir temperature

The geothermal reservoir temperature is calculated using the geothermal gradient of each formation measured through well logging. The highest and lowest temperatures at the boundary between the reservoir and caprocks and bedrocks are calculated as

$$T_{i_\min} = T_0 + \sum_{1}^{i} \left(D_i - D_{i-1} \right) * G_{i_\min} \tag{4}$$

$$T_{i_\max} = T_0 + \sum_{1}^{i} \left(D_i - D_{i-1} \right) * G_{i_\max} \tag{5}$$

where T_{i_min} and T_{i_max} are the lowest and highest temperatures of the bedrock, respectively; D_0 is the burial depth of the constant temperature zone, D_1 is the burial depth of the Quaternary, and D_i is the burial depth of the ith formation counted from the Quaternary; and G_{i_min} and G_{i_max} are the minimum and maximum geothermal gradients of the ith formation, respectively. The most probable temperature of the reservoir bedrock is approximated based on the mean thickness of the formations, which is calculated as

$$T_{i_\mathrm{mod}} = T_0 + \sum_{1}^{i} \left(D_{i_mean} - D_0 \right) * G_{i_\mathrm{mod}} = T_0 + \sum_{1}^{i} \left(\frac{V_i}{A_i} - D_0 \right) * G_{i_\mathrm{mod}} = T_0 + \sum_{1}^{i} \left(\frac{V_i}{(A_{i_u} + A_{i_d})/2} - D_0 \right) * G_{i_\mathrm{mod}} \tag{6}$$

where T_{i_mod} is the most probable temperature of the reservoir bedrock; D_{i_mean} is the mean burial depth of the bedrock of the ith formation; G_{i_mod} is the most probable geothermal gradient of the ith formation (approximated by the mean measured geothermal gradient); V_i is the formation volume of the ith formation; and A_i, A_{i_u} and A_{i_d} are the area of the ith formation, the caprock and bedrock of the ith formation, respectively.

2.3 Other parameters

Other parameters in the volume method are determined as follows: the reference temperature T_0 and the burial depth of the constant zone (D_0) can be determined either by well logging or by using data from previous studies; the rock and water densities (ρ_r and ρ_w, respectively), the rock porosity (Φ) and the specific heat capacity of the rock and water (c_r and c_w, respectively) can be determined either by measurements or by using empirical values recommend by DZ40–85, while the recovery factor value (R_E) is chosen according to DZ40–85.

3. CASE STUDY

3.1. Geologic setting of the Xiongxian Geothermal field

Xiongxian city is located in the center of Hebei Province in north China with a distance of 108 km to Beijing and 100 km to Tianjin, and covers an area of ca. 518 km^2. The elevations of the area are 4 to 25 m.a.s.l. The Xiongxian Geothermal Field is situated in the Niutuozhen uplift, which is located north of the Jizhong Depression, a part of the North China basin (Fig. 2). The boundary of the Niutuozhen Uplift consists of four main faults, i.e., the Niudong Fault, the Niunan Fault, the Rongcheng Fault and the Daxing Fault, which were created by folding movement from the Late Jurassic to the Cretaceous during the Himalayan movement. The Xiongxian Geothermal Field is located in the southwestern part of the Niutuozhen Geothermal System. The main geothermal reservoirs are porous Tertiary sandstone and karst-fissured Precambrian dolomite bedrock. From younger to older, the strata are described as follows: 1) Cenozoic: the Quaternary deposits spread over the whole territory of Xiongxian. The lithology is mainly sandy loam and clay interlayered with sand. The strata are found in the depth range of ca. 380~500 m. Quaternary strata overlies Tertiary strata and are in parallel and unconformable contact with each other. The Neogene Minghuazhen Formation consists of mudstone, sandstone and pebbled sandstone in its upper part, and mudstone and grey sandstone in the lower part, with a thickness of about 500-600 m in the center of the Niutuozhen Uplift, and up to 1000 m in the two wings. The upper strata of Minghuazhen Formation spread over Xiongxian. The axis of the Niutuozhen Uplift did not get deposits of the lower strata of Minghuazhen Formation, the deposition occurred at the wings where the units get thicker. The Guantao Formation, the Dongying Formation, the Shahe Formation and the Kongdian Formation from the Tertiary, only exist in the Baxian Depression but not in the Xiongxian Uplift. 2) Proterozoic: The Jixian System includes the Tieling Formation, the Hongshuizhuang Formation and the Wumishan Formation. Among them, the Wumishan Formation spreads over most of the territory of Xiongxian and directly underlies Tertiary strata of the Niutuozhen Uplift. It is composed of dolomite and muddy dolomite and the total thickness is 1045-2620 m. The Changcheng System strata underlie the Jixian System strata. The thickness of the Gaoyuzhuang Formation of the Changcheng System is approximately 1000 m; and the rest of the formations in the Changcheng System do not exist in the Niutuozhen Uplift. 3) Archaeozoic: It is composed of gneiss and granulites and underlies the Changcheng System strata and the footwall of the Niudong Fault. The depth is more than 3500 m (Huang, 2012).

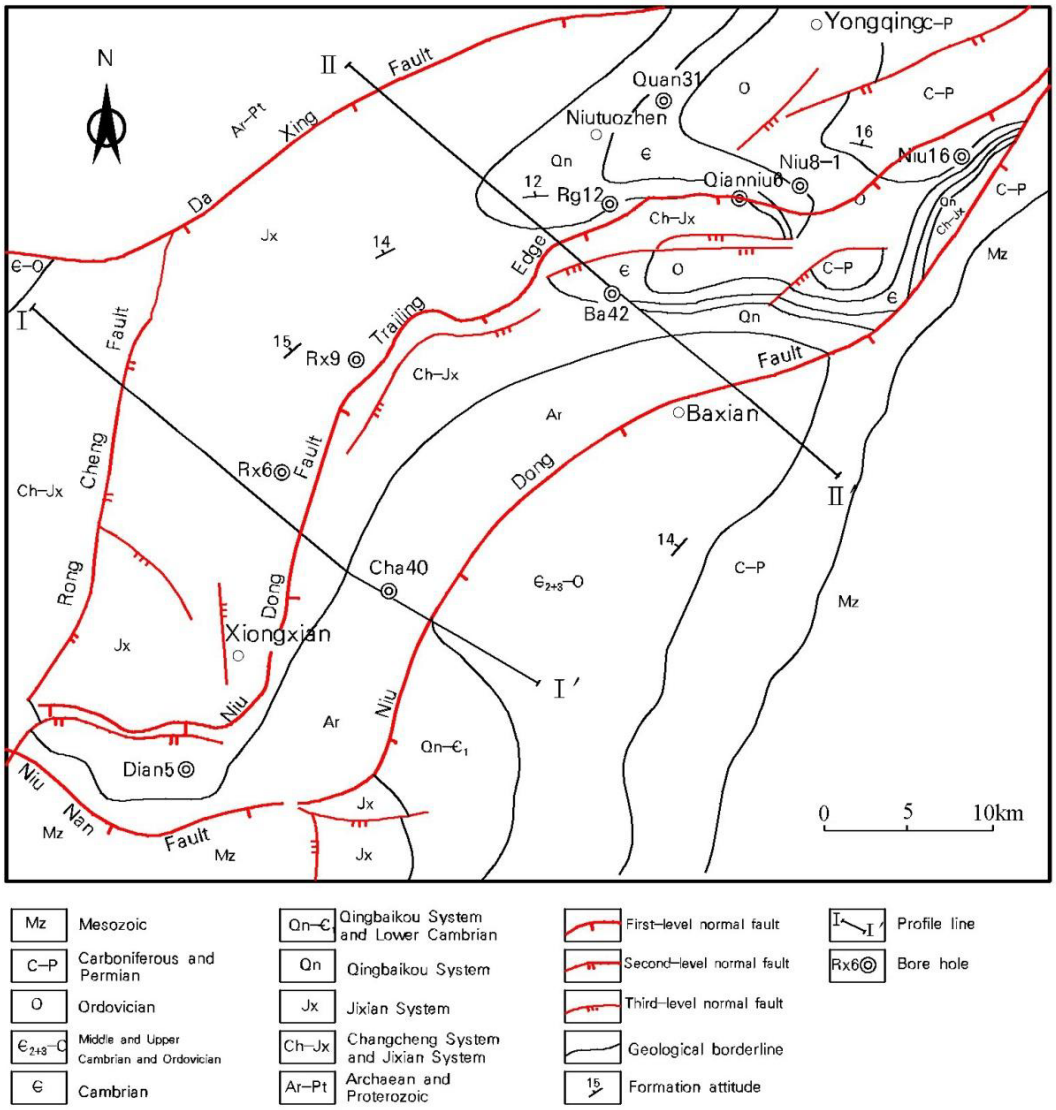

Fig. 2 Geological map of the bedrock of the Niutuozhen Uplift (Han, 2008)

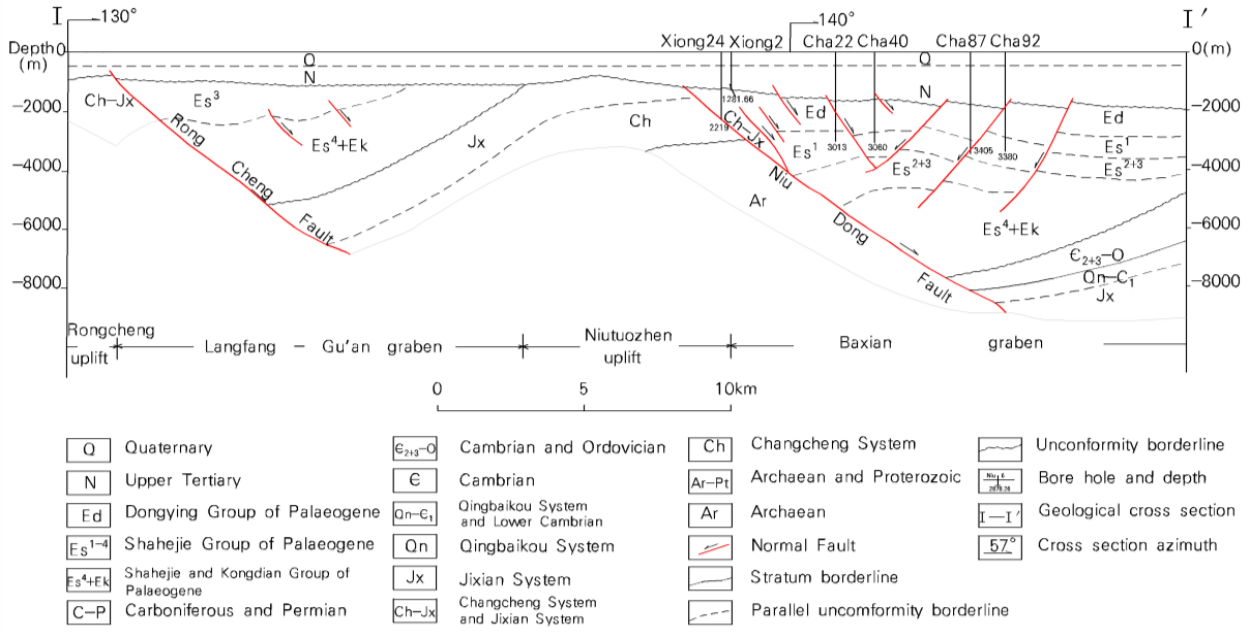

Fig. 3 Geological cross-section (I-I' in Fig. 2) through the Niutuozhen Uplift (Wang, 2009)

3.2. Geological model of the Xiongxian Geothermal Field

In the assessment, we estimate the stored and recoverable heat energy of the Tertiary and bedrock reservoirs within the depth of 3000 m. According to the strata distribution, the geological model of the Xiongxian Geothermal Field is built using Surpac. Based on the data from oil exploration and geothermal surveys in the area and nearby, the geological solids of the reservoirs and the caprock are built (Fig. 4). For convenience of the calculation, the field is divided into two parts, i.e., the eastern part and the western part, which are separated by the boundary of the bedrock at 3000 m depth and the Tertiary in the Baxian Depression. The eastern part contains only the Tertiary reservoir, while the western part consists of both the Tertiary and the bedrock reservoirs (Fig. 4).

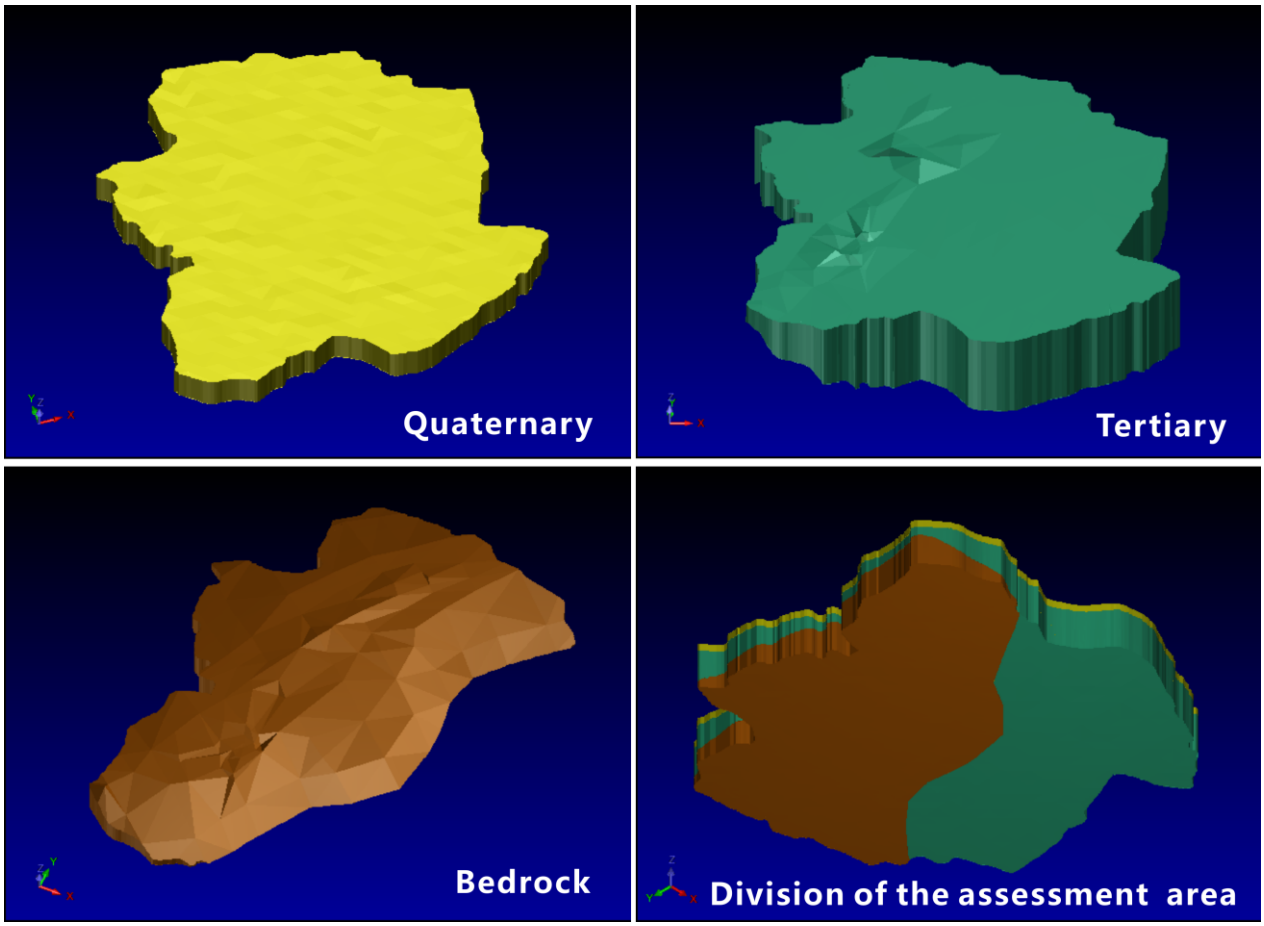

Fig. 4 Geological model of the Xiongxian Geothermal Field

3.3. Characteristic values of the parameters

3.3.1 Reservoir temperature

Based on data form previous studies, the reference temperature T_0 and the burial depth of the constant zone D_0 in the region of Xiongxian are 14.5 ℃ and 30m, respectively (Chen, 1988). The geothermal gradients of the reservoirs and caprock are determined from well logging (Table 1). The characteristic values of the reservoir temperatures are calculated and listed in Table 2 (Yang et al., 2014).

Table 1 Characteristic values of the geothermal gradient for the Xiongxian Geothermal Field

Formation	Characteristic values of the geothermal gradient (℃/hm)		
	G_{i_min}	G_{i_max}	G_{i_mod}
Quaternary	2.95	9.29	5.24
Tertiary	3.20	6.73	4.67
Bedrock	1.09	2.29	1.59

Table 2 Characteristic values of the reservoir temperature for the Xiongxian Geothermal Field

Assessment area	Reservoir	Characteristic values of the reservoir temperature (ºC)		
		$T_{_min}$	T_{i_max}	T_{i_mod}
Western part	Tertiary	40.00	225.34	58.18
	Bedrock	40.00	225.34	93.05
Eastern part	Tertiary	40.00	225.37	96.16

3.3.2 Reservoir volume

Characteristic values of the reservoir volume with geothermal resources above 40 ºC are calculated and are listed in Table 3.

Table 3 Characteristic values of the reservoir volume for the Xiongxian Geothermal Field

Assessment area	Reservoir	Characteristic values of the reservoir volume（km^3）		
		minimum	maximum	mean
Western part	Tertiary	165	289	264
	Bedrock	488	497	497
Eastern part	Tertiary	452	538	523

3.3.3 Other parameters

Since the physical properties data of the reservoir rocks for the Xiongxian Geothermal Field are sparse, the data from the region of Tianjin are used as an approximation (Chen, 1988; Chen et al., 1991; Zhang et al., 1995; Lin et al., 2002). The rock porosity is collected from the logging data of 10 geothermal wells, the most probable value is determined as the thickness weighted average of the porosities measured for each test section (Table 4).

Table 4 Characteristic values of the physical properties of the reservoir rocks for the Xiongxian Geothermal Field

Reservoir	ρ_r (kg/m^3)			c_r (J/g/K)			Φ (%)		
	minimum	maximum	mean	minimum	maximum	mean	minimum	maximum	mean
Tertiary	1910.0	2690.0	2245.0	0.82	1.04	0.91	26.9	41.91	33.44
Bedrock	2702.0	3060.0	2881.0	0.86	1.02	0.94	0.47	13.91	4.72

The water density (ρ_w) and specific heat capacity (c_w) is taken from DZ40–85 as 1000.0 kg/m^3 and 取 4.18 J/g/K, respectively, and the recovery factor (R_E) for the porous Tertiary sandstone and karst-fissured Precambrian dolomite bedrock reservoirs are 0.25 and 0.15, respectively.

3.4. Results and discussions

The Monte Carlo simulation is conducted using the risk analysis tool @RISK, with the inputs of the characteristic values of the triangular distribution of the parameters in the volume method, the stored and recoverable heat energy of the Tertiary and bedrock reservoirs are calculated with a sampling number of 10,000. The results are listed in Table 5.

The stored heat reserves within the buried depth of 3000 m of the Tertiary sandstone reservoir are calculated to be 7.28±2.16G TCE (1σ). While the underlying Precambrian dolomite bedrock reservoir to be 4.96±1.86G TCE (1σ). The recoverable heat of the Tertiary and the Precambrian dolomite bedrock reservoir are $5.3\pm1.6\times10^8$ t and $2.2\pm0.8\times10^8$ t, respectively.

In order to make a comparison of the performance of the MCGM and traditional volumetric method (TVM), we also evaluated the potential of the reservoirs base on the TVM. In the calculation, the thickness (D), geothermal gradient (G_i), density (ρ_r), specific heat capacity (c_r) and porosity (Φ) of the caprock and reservoirs are represent by the mean value estimated by borehole, logging or rock testing data (Table 6). The heat in the reservoir and recoverable heat was calculated by equations 2 and 3, respectively. The reservoir temperature in equation 2 is determined by the mean value of the temperatures at the bottom and the top boundary of the

reservoirs, which are 55.6 ℃, 93.1 ℃ and 93.0 ℃ for the western and eastern part of the Tertiary and bedrock reservoir, respectively. The results are listed in Table 7.

Table 5 Potential of the Xiongxian Geothermal Field (1σ) based on MCGM

Reservoir	Heat in the reservoir (10^{16} kJ)	Standard coal equivalent (10^8 t)	Recoverable heat (10^{16} kJ)	Standard coal equivalent (10^8 t)
Tertiary (Western part)	6.3±2.9	21.5±10.0	1.6±0.7	5.4±2.5
Tertiary (Eastern part)	15.0±5.6	51.3±19.1	3.8±1.4	12.8±4.8
Tertiary (Total)	21.3±6.3	72.8±21.6	5.3±1.6	18.2±5.4
Bedrock	14.5±5.4	49.6±18.6	2.2±0.8	7.4±2.8
Total	35.8±8.3	122.4±28.5	7.5±1.8	25.6±6.1

Table 6 Parameters used in the potential assessment of the Xiongxian Geothermal Field based on traditional volumetric method

Formation	A (km^2)	D (m)	G_i (℃/hm)	ρ_r (kg/m^3)	c_r (J/g/K)	Φ (%)
Quaternary	518.4	445.0	5.24	—	—	—
Tertiary (Western part)	307.4	941	4.67	2245.0	0.91	33.44
Tertiary (Eastern part)	211.0	2551	4.67	2245.0	0.91	33.44
Bedrock	518.4	1618	1.59	2881.0	0.94	4.72

Table 7 Potential of the Xiongxian Geothermal Field (1σ) based on traditional volumetric method

Reservoir	Heat in the reservoir (10^{16} kJ)	Standard coal equivalent (10^8 t)	Recoverable heat (10^{16} kJ)	Standard coal equivalent (10^8 t)
Tertiary (Western part)	3.3	11.2	0.8	2.8
Tertiary (Eastern part)	11.7	39.8	2.9	10.0
Tertiary (Total)	15.0	51.0	3.7	12.8
Bedrock	18.3	62.4	2.7	9.4
Total	33.3	113.4	6.4	22.2

Comparison between the potential assessment results base on the MCGM and TVM shows that the calculated values of the TVM fall in the range of those of the MCGM. As the uncertainty of the characteristic parameters of the geothermal field is taken into consideration, and can be reflected in the assessment results, potential assessment by the MCGM is more reasonable.

4. CONCLUSIONS

The volume method is preferred and has been widely used in the early phases of geothermal development, and the reservoir thermal energy is calculated according to parameters both of reservoir rock and fluids. However, as data are limited and with high uncertainty at early stages of geothermal development, we propose a combined method based on Monte Carlo simulation and geological modeling to characterize both the uncertainty of the temperature and volume of the reservoir.

Supposing both the reservoir temperature and volume have triangle distribution, the characteristic values, i.e., minimum, maximum and most probable (mean or mode) values are determined through geological modeling. The geological solids of both the reservoir and caprock are built first, and then the 40 ℃ isothermal surfaces are determined through DTM operations according to the minimum, maximum and most probable geothermal gradient of the reservoirs, respectively. By interception of the reservoir solids with the isothermal surfaces, the characteristic values of the reservoir volume are determined. The characteristic values of the

reservoir temperature are also obtained through DTM operations according to the characteristic values of the geothermal gradient. Finally, the characteristic values of each parameter are used to define its distribution in Monte Carlo simulations, and the stored heat reserves of the reservoirs are calculated.

Taken Xiongxian Geothermal filed of China as a case study, the stored heat reserves above buried depth of 3000 m of the Neogene sandstone reservoir is calculated to be 7.28±2.16G TCE（1σ）, while the underlying Precambrian carbonate reservoir to be 4.96±1.86G TCE（1σ）.

The method is useful in the determination of the reservoir temperature and volume, especially when the geological structures become complicated, thus improve the reliability of the geothermal resource assessment.

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