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ORIGINAL ARTICLE

Estimating geothermal resources in Bohai Bay Basin, eastern China, using Monte Carlo simulation

Zhuting Wang[1,2,3] · Guangzheng Jiang[1,2,3] · Chao Zhang[1,2,3] · Xianchun Tang[4] · Shengbiao Hu[1,2,3]

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Abstract

Geothermal energy is being widely exploited as a clean and renewable energy resource, and accurate assessments of potential resources can help us make reasonable planning and utilization of them. The volumetric method has been widely used in assessing geothermal resources owing to its simplicity and convenience. However, this method does not take into account the uncertainties of the input parameters involved, instead assigning a series of specific parameter values for each reservoir. Here, a Monte Carlo simulation approach was used to reduce these uncertainties while applying the volumetric method to estimate the geothermal resources of Bohai Bay Basin in eastern China. The basin contains two main types of thermal reservoirs: sandstone and carbonate. In applying Monte Carlo analysis to these reservoirs, the triangular and uniform distribution models for input parameters were used, and simulations were run with 1000–5000 iterations. Results indicate capacities of (1.182–2.283) × 10^{21} J (most likely 1.74 × 10^{21} J) and (1.299–2.546) × 10^{21} J (most likely 1.937 × 10^{21} J) for the Minghuazhen and Guantao sandstone reservoirs, respectively, and a capacity of (0.608–1.254) × 10^{21} J (most likely 8.450 × 10^{20} J) for the carbonate reservoir, finally, a range value (3.466–5.553) × 10^{21} J (most likely 4.400× 10^{21} J) for the whole Bohai Bay Basin.

Keywords Geothermal resource · Thermal reservoir · The volumetric method · Monte Carlo simulation · Bohai Bay Basin

Introduction

With the depletion of fossil fuels and the intensification of environmental pollution, geothermal energy, as a clean and renewable energy resource, is receiving increasing attention. China, with the most abundant medium–low temperature geothermal resources in the world, has made significant progress in utilizing such resources. Bohai Bay Basin, located in eastern China, is a rift basin with a high thermal background (Hu et al. 2000). Wells intended for oil and gas production within the basin have facilitated the exploration and utilization of geothermal resources. Many geothermal fields have been developed for local domestic heating. However, overexploitation of geothermal resources in some areas has led to the groundwater levels dropping sharply and direct discharge of geothermal water after use has caused soil pollution, because the groundwater is under high temperature and pressure conditions, it has a strong ability to dissolve the chemical substances from the surrounding rocks, when the groundwater is directly discharged at the surface rather than geothermal reheating. Some of these chemical substances may be harmful to the human body and can cause soil pollution (Hreinsson 2007; Ma et al. 2006).

Accurate assessments of geothermal resources help us to ensure correct planning and exploitation of such resources. Geothermal resources in some areas of Bohai Bay Basin have been estimated using the volumetric method, and temperature distribution maps at different depths have been compiled (Lin et al. 2013; Wang et al. 2012; Ying 2015). However, the volumetric method does not consider the uncertainties in the parameters involved but rather assigns a specific value for each reservoir characteristic, with results

✉ Zhuting Wang
wangzhuting123@163.com

[1] State Key Laboratory of Lithosphere Evolution, Institute of Geology and Geophysics, Chinese Academy of Science, Beijing 100029, China

[2] University of Chinese Academy of Science, Beijing 100049, China

[3] Institutions of Earth Science, Chinese Academy of Science, Beijing 100029, China

[4] Chinese Academy of Geological Sciences, Beijing 100037, China

representing ideal situations. The complexity of geological conditions is such that it is inappropriate to simply divide thermal reservoir layers into blocks and to use sets of parameters for each block. For geothermal systems with a significant natural thermal influx, the volumetric stored-heat method may underestimate resource capacity (Quinao and Zarrouk 2018).

The present study reassesses the geothermal resources of Bohai Bay Basin. The oceanic part of the basin, including Bozhong Depression located within the Bohai Sea, was excluded from the study because of the difficulties in data collection. Temperature measurements were carried out for different sub-structural units within the basin, with new temperature–depth data providing temperature ranges for different thermal reservoirs, which is one of the most important parameters in resource assessment. Densities and specific heats of different rock types were also determined, as these may impact geothermal resources. Based on these parameters, the geothermal resource potential beneath the subsurface was estimated using the volumetric method, with uncertainties in parameters such as reservoir area and temperature being assessed by Monte Carlo simulation, which takes all parameter uncertainties into account. Monte Carlo analysis is a stochastic simulation approach involving repetitive random sampling of model inputs to produce a collection of random outputs that are then analyzed statistically (Supriyadi et al. 2014). Different distribution models can be applied to estimating parameter uncertainties, such as the triangular distribution model, which specifies the minimum, most likely, and maximum values. Results are given as frequency distributions of energy values, which can then be used to investigate probabilities for each set of calculation results.

Geothermal background and stratigraphic characteristics of the study area

Thermal background of Bohai Bay Basin

Bohai Bay Basin has undergone multiple tectonic movements during the Mesozoic and Cenozoic, including the Yanshan movement, the Himalayan movement, and Pacific Plate subduction. These various movements have caused lithospheric break up and the development of deep faults throughout the basin. The upwelling of mantle material induced by crustal extension and tectonic frictional heat during the most recent tectonic movements have produced a high thermal background in the basin. A recent compilation of heat flow data in continental China indicates an average heat flow of 68.9 mW m^{-2} in the basin, which is higher than both the average heat flow in mainland China (60.4 mW m^{-2}) (Jiang et al. 2016a) and the mean global continental heat flow (64.7 mW m^{-2}) (Davies 2013). The higher heat flow in the basin means that more thermal energy is stored beneath the surface, indicating a potential for geothermal development and utilization. An understanding of heat flow distribution in the basin would help identify the most favorable blocks for geothermal exploitation. The heat flow, mainly composed of heat production in the crust and mantle, heat flow emanating from Earth's core and secular cooling of the mantle, can continue to do so for at least a few billion years (Furlong and Chapman 2013). This makes the geothermal resources sustainable and renewable.

Heat flow distributions in the sedimentary basins of continental China are as follows. Eastern sedimentary basins, such as Songliao and Bohai Bay basins, which have undergone recent (Cenozoic) tectonic movement, have high heat flows of > 65.0 mW m^{-2} (Li et al. 2017). Western sedimentary basins, such as Junggar and Tarim basins, which are intra-cratonic basins developed on relatively old and stable massifs, have heat flows of < 50.0 mW m^{-2}. Central sedimentary basins, such as Ordos and Sichuan basins, where heat flow is influenced by tectonic movement from the east, have heat flows of 50.0–65.0 mW m^{-2} (Fig. 1a) (Hu et al. 2000). Heat flow in Bohai Bay Basin is strongly influenced by basement fluctuations, with basement uplift heat flow being greater than in the depression area of the basin. Some anomalous heat loss blocks are scattered throughout the basin, being influenced by magma intrusion and groundwater in faults (Fig. 1b).

Stratigraphic characteristics of Bohai Bay Basin

The stratigraphic characteristics of Bohai Bay Basin are controlled mainly by tectonic movements, especially the most recent ones. According to previous studies, Bohai Bay Basin has undergone four periods of tectonic movement since the Archean (Chang et al. 2016; Liu 2016; Qi et al. 2003; Qiu et al. 2017), leading to the uplift and erosion of strata. Paleozoic and Mesozoic tectonic movements resulted in the removal of some strata from almost the entire basin, with Cenozoic sedimentary cover unconformably overlying the Proterozoic strata. Rock types of the Cenozoic sedimentary layers are mainly sandstone and siltstone. Their low permeability and thermal conductivity inhibit heat loss, with more thermal energy being stored in the thermal reservoir. Proterozoic rock types are mainly dolomites with high thermal conductivity and permeability, with groundwater convection causing rapid heat transfer to the bottom of the sedimentary layer, producing geothermal resources convenient for exploitation. Faults induced by tectonic movements are well developed in the Proterozoic strata, with the depths of some reaching the basement and enabling sustainable deep energy transfer to the thermal reservoir (Li et al. 2014; Wang

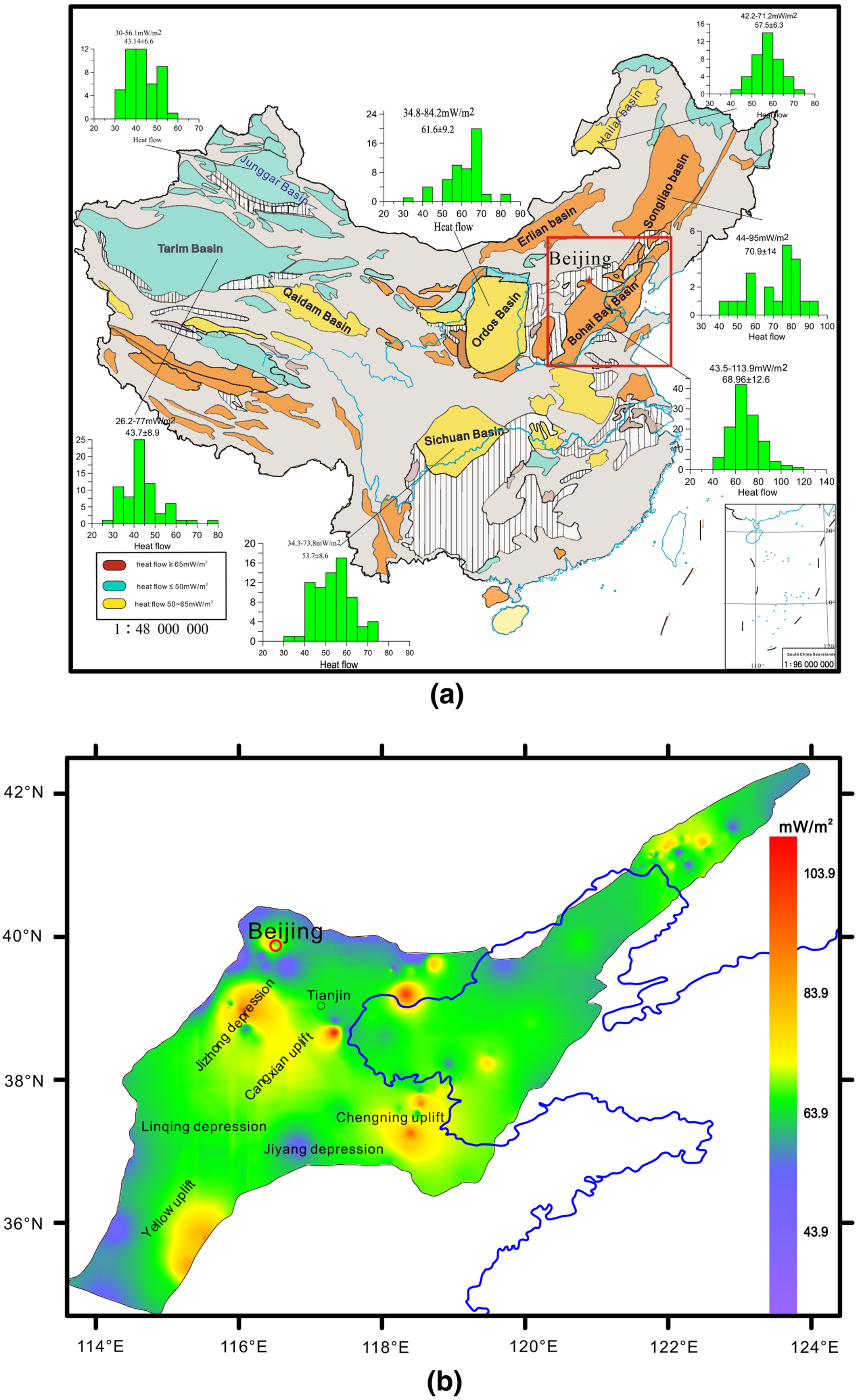

Fig. 1 Thermal background in Bohai Bay Basin

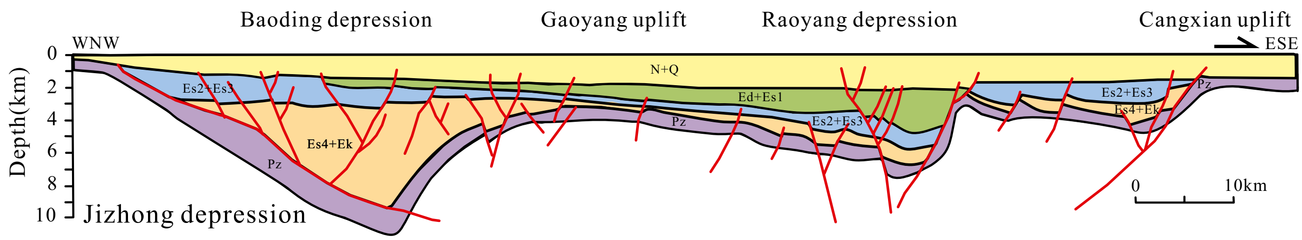

Fig. 2 Stratigraphic characteristics of Bohai Bay Basin (Liu 2016; Zhang 2014). Formation symbols: N + Q represent the Neogene and Quaternary strata, Ed is Dongyingzu strata in Eocene, Es 1, 2, 3, 4 are Sha 1, 2, 3, 4 duan strata in Eocene, Ek is Kongdianzu strata in Eocene, Pz is the Proterozoic strata, and the red line represents the developing faults

et al. 2019). Tectonic movements have also caused the uneven distribution of the basement (Fig. 2). All these stratigraphic characteristics are conducive to thermal reservoir development.

Types of thermal reservoir

Thermal reservoirs in Bohai Bay Basin can be divided into two types according to stratigraphy: Cenozoic reservoirs where rock types are mainly sandstone and siltstone, and carbonate reservoirs containing dolomites.

On the basis of lithology, temperature, and other indicators, Cenozoic thermal reservoirs can be divided vertically into the Minghuazhen and Guantao reservoirs, with both being developed in Neogene strata (N) at depths of 350–2000 m (Fig. 2). The Guantao reservoir with its depth ranging from 350 to 1800 m is deeper than the Minghuazhen reservoir (1000–2000 m), and thus with a correspondingly higher temperature (Wang et al. 2003; Ying 2015). The Cenozoic thermal reservoirs can also be divided into different blocks in the horizontal dimension on the basis of the characteristics of different sub-tectonic units within Bohai Bay Basin (blocks A–F in Fig. 3). The geothermal resources of the northeastern and southern parts of Bohai Bay Basin, such as Bozhong Depression in Bohai Bay, were not assessed in this study because of insufficient data being available. The distribution model of Cenozoic thermal reservoirs is presented in Fig. 3.

The lithology of the carbonate thermal reservoir comprises mainly dolomite contained in Proterozoic strata, with the reservoir being distributed mainly within tectonic uplift units (Fig. 2). As a medium-to-low temperature reservoir, the carbonate reservoir provides optimal conditions for resource exploitation with high coefficients of geothermal recovery. The thickness of the overlying sedimentary layer is small, and reservoir burial depth is 1000–3000 m except in areas such as Jizhong Depression, where the depth can be less than 1000 m, which is convenient for extraction. The development of karst fissures inside the thermal reservoir provides a good channel for groundwater activities, and the heat energy from the deep depth can be quickly transferred to the bottom of the sedimentary cover layer as the manner of convection, which leads the thermal reservoir to having a high temperature. Water content and permeability aid the extraction of groundwater and reinjection (Chen 1988). The distribution of the carbonate thermal reservoir in Bohai Bay Basin is shown in Fig. 4. Other area in Bohai Bay basin may find this kind of reservoir with the survey and development of geothermal resources.

Methodology

Volumetric method

As one simple and convenient method, the volumetric method has been widely used in the evaluation of the geothermal resources potential. The volumetric method can generally calculate the total thermal energy which is stored in the subsurface rock and the pore water, and this thermal energy can be extracted from a specified reservoir and reservoir temperature for heating and other purposes (Muffler and Christiansen 1978; Shah et al. 2018). The basic equations used in the volumetric method are:

$$Q_r = Ah\left[\rho_r C_r (1-\phi)\left(T_r - T_s\right)\right], \tag{1}$$

$$Q_w = Ah\left[\rho_w C_w \phi\left(T_r - T_s\right)\right], \tag{2}$$

where Q_r and Q_w represent thermal energy stored in rock and pore water, A is the area of the thermal reservoir, h is the thickness of the reservoir, ρ_r and ρ_w are the respective densities of rock and water in the reservoir, C_r and C_w are the heat capacities of rock and water in the reservoir, ϕ is rock porosity, T_r and T_s are the respective average temperatures of reservoir and surface. In the volumetric method, these parameters are given specific values that do not take into account the complexity of stratigraphic features. Quantification uncertainty of the parameters can be dealt quite well using a Monte Carlo simulation, because the Monte Carlo simulation is designed as a software which can simulate the probability distribution model for the input parameters uncertainty, and each result is sent to a bin to be compiled

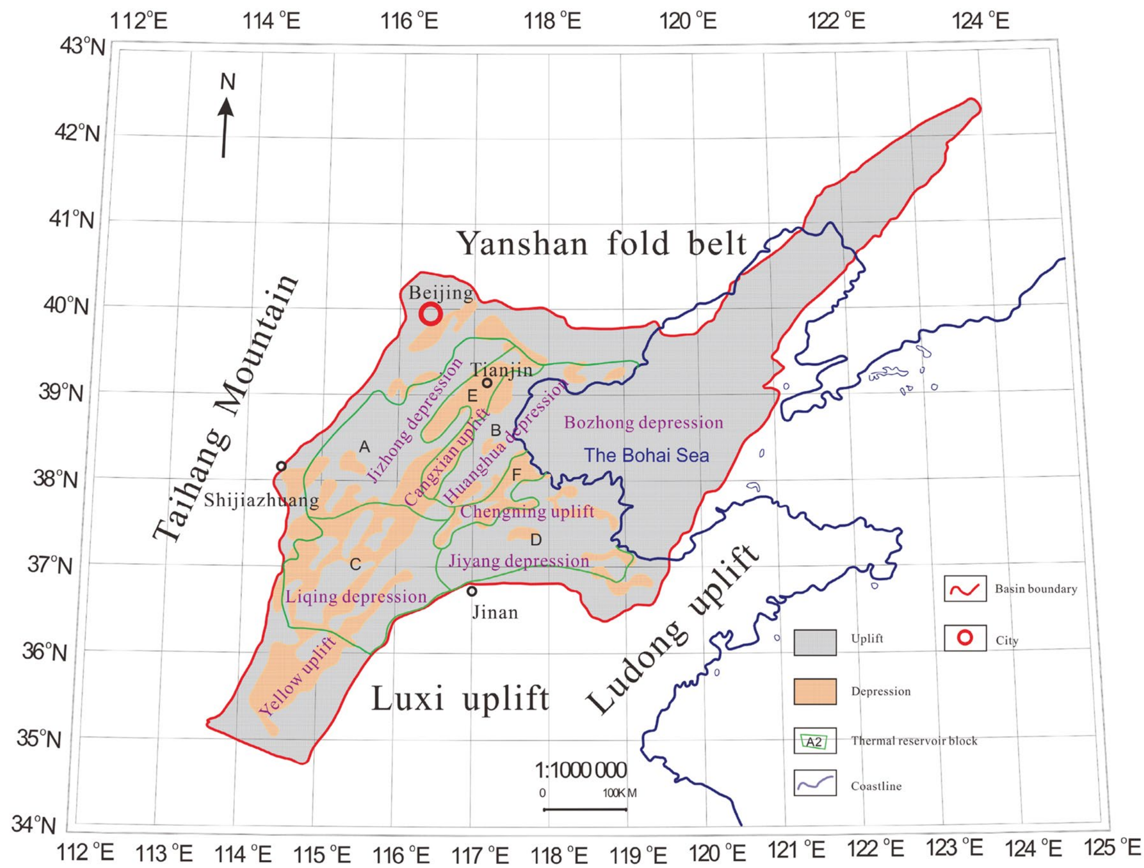

Fig. 3 Distribution of Cenozoic thermal reservoirs in Bohai Bay. The gray areas represent the tectonic depression unit, orange areas indicate tectonic uplift, green lines indicate the different blocks of the Cenozoic thermal reservoir, while red and blue lines mark the boundary of Bohai Bay Basin and the coastline of China, respectively

for the frequency distribution (Guo 2008; Shah et al. 2018), as described in section "Monte Carlo simulation".

Monte Carlo simulation

Monte Carlo simulation is a method used for statistically analyzing the probability functions of random events. Through the random selection of input parameters and the use of mathematical models based on a series of formulae, each set of the input parameters can yield a result, and the analysis system can then interpret the calculation results and finally express the possibility of the calculation results which correspond to different input parameters (Arkan 2003; Yang et al. 2015). The method goes through the following steps: sets of input and target parameters are defined, relationships between input and output parameters are defined on the basis of mathematical models, different parameter distribution models are set for the input parameters, the number of iterations is set, and the simulation then analyzes the calculated results and provides probability distribution functions for each result (including cumulative frequency distributions).

Monte Carlo software provides various distribution models for input parameters, including uniform, lognormal, normal, and triangular distributions, with each model having its own frequency distribution (Fig. 5) (Shah et al. 2018). Due to the insufficient data in this study, the relatively simple distribution model was chosen. Here, the uniform distribution model was used, in which parameters are treated as constant numbers, as well as the triangular distribution model, which is defined by three points—the minimum, most likely, and maximum values. Before the simulation, the number of iterations can be selected, the greater the number of iterations, the more accurate will be the result (and the longer the computation time). Taking accuracy and time into account, the number of iterations used here was 1000–5000 (Supriyadi et al. 2014).

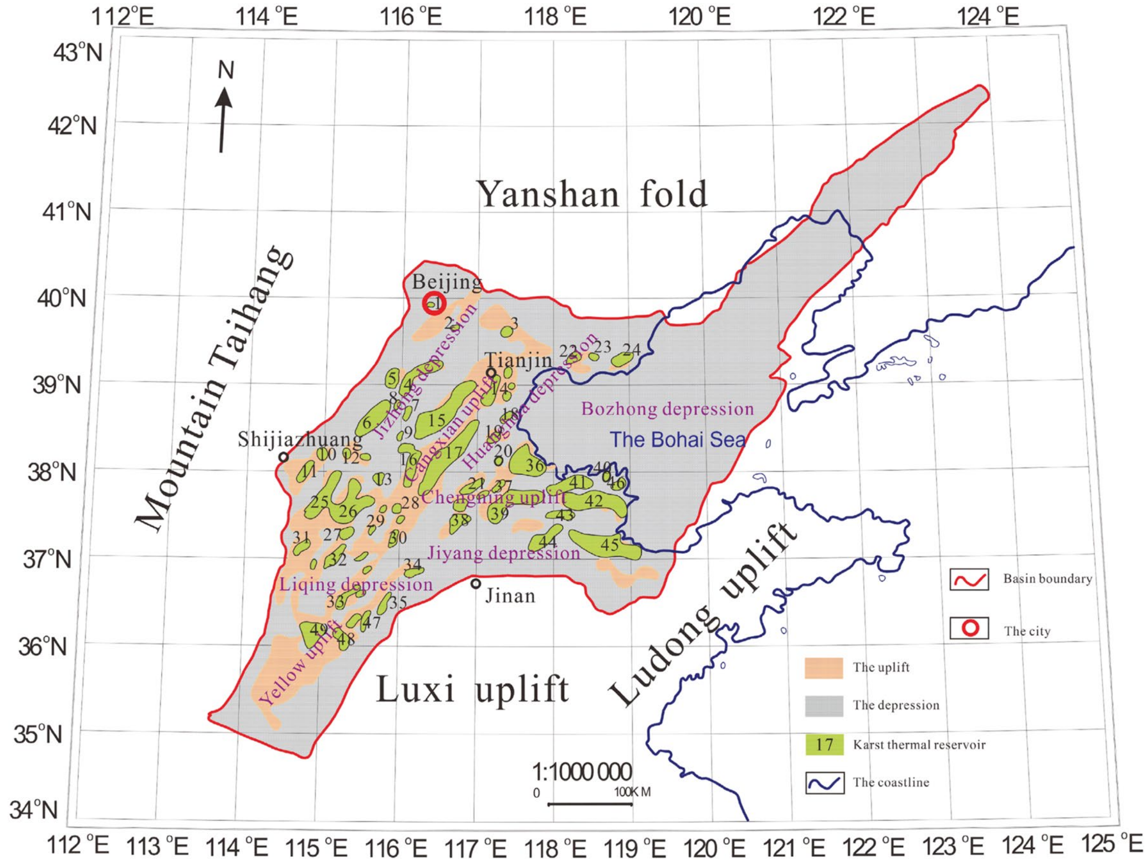

Fig. 4 Distribution of the carbonate thermal reservoir. The gray areas represent the tectonic depression unit, orange areas indicate tectonic uplift, green areas indicate the carbonate thermal reservoir which are ordered by different numbers, and red and blue lines mark the boundary of Bohai Bay Basin and the coastline of China, respectively

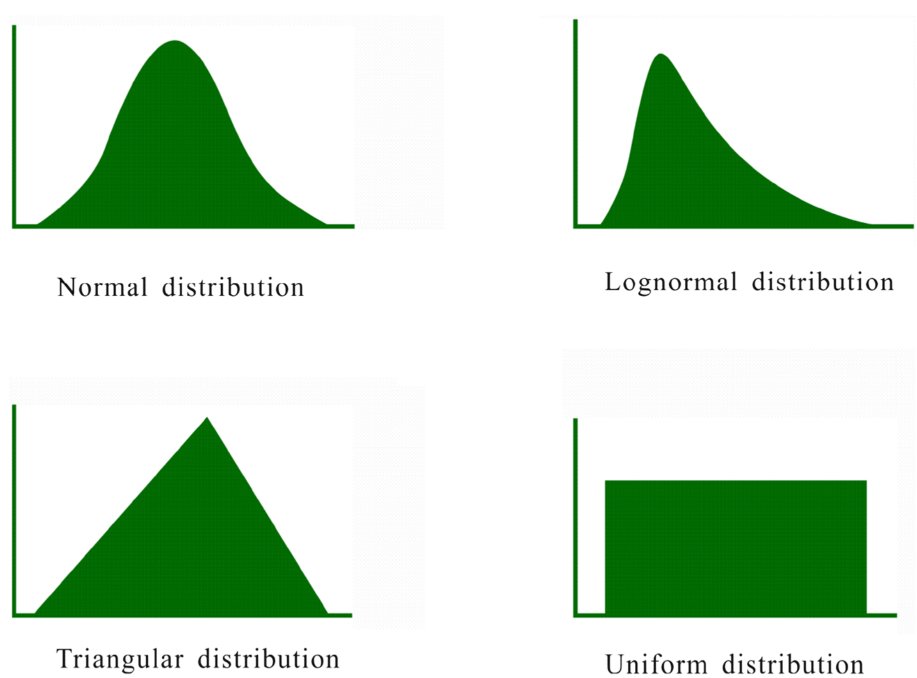

Fig. 5 Distribution models of input parameters

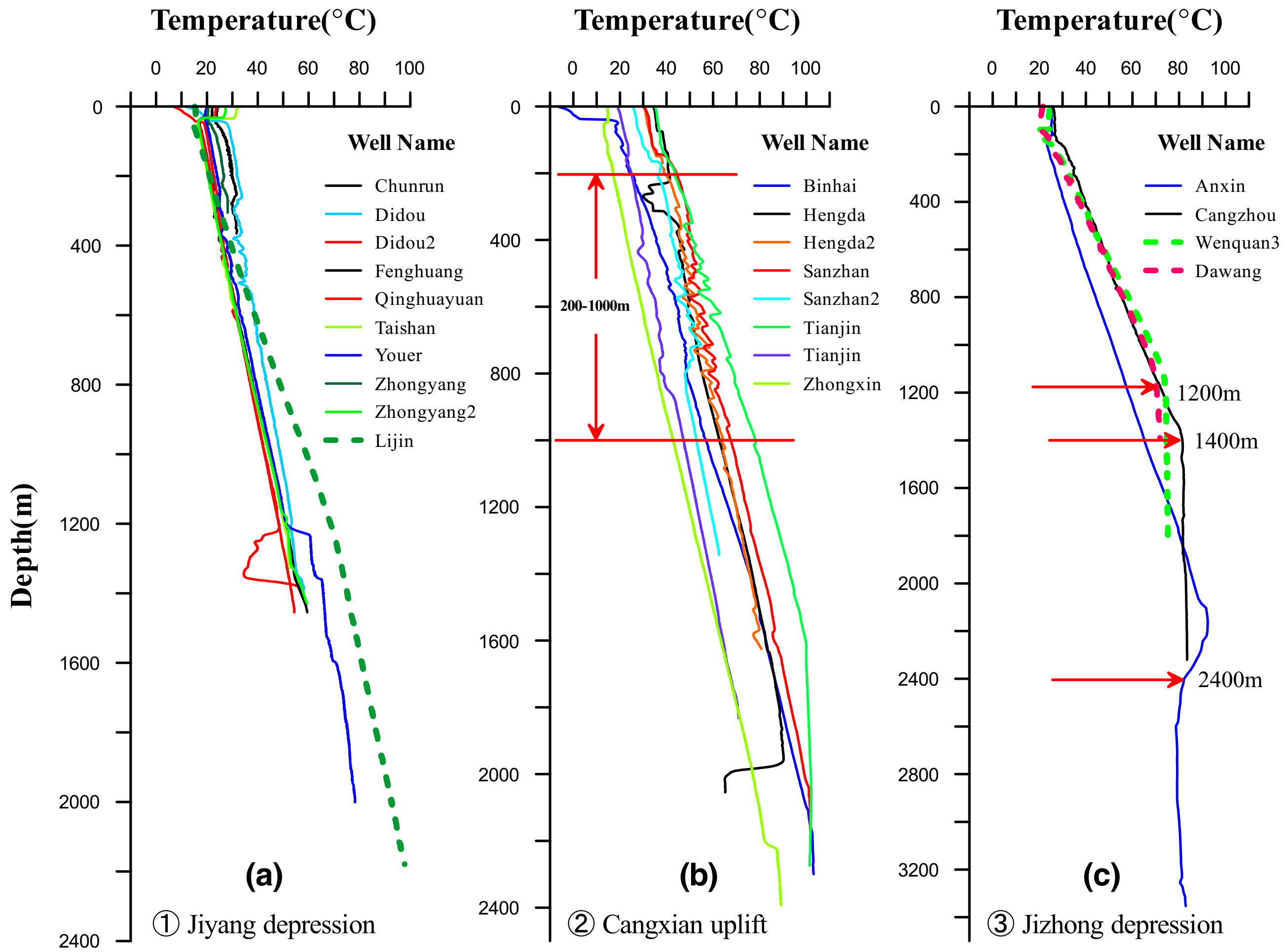

Fig. 6 Temperature–depth profiles obtained at Bohai Bay basin

Database

Temperature–depth profiles

Temperature is an important variable in the assessment of geothermal resources, because it directly affects the geothermal resource potential of a thermal reservoir. Borehole temperature measurements are one of the most effective methods of obtaining information on reservoir temperatures, and considering such an important role of the temperature played during the evaluation of the geothermal resources, the borehole temperature measurement work was carried out within the sub-structural units of the Bohai Bay Basin to obtain the real temperature of the thermal reservoir using a cable system, consisting of a 42.9-mm-diameter sensor (max. temperature 176 °C, max. pressure 124 MPa) and a 5000-m-long cable (2.54 mm single conductor). The sensor contains a platinum resistance temperature detector that exploits and optimizes the tendency of metallic conductors to exhibit a change in resistance with temperature, with a response time of less than 2 s. The system allows temperature recording to a sensitivity of 0.01 °C at a limiting accuracy of 0.1 °C (Jiang et al. 2016b). Temperature measurement sites were concentrated in the Jiyang Depression (ten temperature–depth logs), Cangxian Uplift (eight logs), and Jizhong Depression (four logs). The results are shown in Fig. 6, in which solid lines represent the profiles of the present study, and dotted lines represent previously published data (Jiang et al. 2016b; Li et al. 2014). From the temperature–depth profile data, analysis shows that the sub-structural units of the Bohai Bay Basin have a higher present geothermal field in which the geothermal gradient is around 35 °C/km within the sedimentary cover layer. On the other hand, each sub-structural has its own characteristics. For example, the temperature–depth profiles of Cangxian Uplift are affected by groundwater, with profiles fluctuating markedly at depths of 200–1000 m (Fig. 6a), whereas in Jizhong Depression, temperature is relatively constant below a certain depth, like the Anxin well with the depth

Table 1 Parameters of the Minghuazhen thermal reservoir (Chen 1988; Liang et al. 2010; Yan et al. 2001; Zhao et al. 2016)

Tectonic unit	Symbol for geothermal field	Area (km^2)	Thickness (m)	Porosity (%)	Temperature of the thermal reservoir (°C)	Rock density ($kg\ m^{-3}$)	Specific heat of rock ($J\ kg^{-1}\ °C$)	Water density ($kg\ m^{-3}$)	Specific heat of water ($J\ kg^{-1}\ °C$)
Jizhong depression	A	21,970	180–620 (420)	30–33 (31)	31.0–43.0 (36.0)	2574–2673 (2623)	778–876 (827)	1000	4180
Huanghua depression	B	12,150	270–510 (390)	24–26 (25)	32–40 (36)	2574–2673 (2623)	793–830 (811)	1000	4180
Linqing depression	C	27,970	160–380 (250)	29–35 (31)	36–37.5 (36)	2574–2673 (2623)	761–834 (797)	1000	4180
Jiyang depression	D	17,610	80–160 (120)	29–32 (30)	36–38.5 (37)	2574–2673 (2623)	781–875 (828)	1000	4180
Cangxian uplift	E	5690	300–650 (500)	15–32 (25)	35–50 (42.5)	2574–2673 (2623)	754–832 (793)	1000	4180
Chengning uplift	F	4323	200–300 (250)	24–36 (30)	40–46 (43)	2574–2673 (2623)	783–875 (829)	1000	4180

Most likely values are provided in parentheses

of 2400 m and Cangzhou well with the depth of 1400 m (Fig. 6c). Although the temperature-logging points do not cover Bohai Bay Basin evenly, they can still reflect the temperature distribution characteristics of the thermal reservoir.

Other simulation input parameters

Parameters such as thermal reservoir temperature, rock density, specific heat, reservoir thickness and area, and reference temperatures are all needed when combining the volumetric and Monte Carlo methods to calculate geothermal resources. Geological complexity dictates that these parameters have different ranges of values in different structural units, and the Monte Carlo method can estimate uncertainties in their values (Han et al. 2015; Shah et al. 2018; Supriyadi et al. 2014). When applying Monte Carlo simulation in the geothermal resource assessment (based on Eqs. 1 and 2), the uniform distribution model was used for heat storage area (A), water density (ρ_w), reference temperature (T_s), and the specific heat of water ($C_{\rho w}$) (values of ρ_w, T_s, $C_{\rho w}$ are defined by Ministry of Geology and Mines of the People`s Republic of China), whereas the triangular distribution model was used for thermal storage thickness (H), heat storage temperature (T_R), porosity (ϕ), rock density (ρ_r), and specific heat ($C_{\rho r}$). To simplify the calculation and considering the complexity chemical composition of groundwater, specific heat and density of groundwater are considered as independent of temperature. In the Minghuazhen thermal reservoir thickness term for Jizhong Depression (Table 1), the 180–620 m thickness value range represents the possible thickness distribution range and 420 m which is in the parentheses is the most likely value. Where there are insufficient data, the average of the maximum and minimum values was used as the most likely value with the triangular distribution model.

In the present study, temperatures of thermal reservoirs were obtained from the temperature–depth profile measurements conducted mainly within Jiyang Depression, Cangxian Uplift, and Jizhong Depression. No measurements were carried out in other sub-tectonic units, such as Huanghua Depression, Linqing Depression, and Chengning Uplift, so previously published data were used. Rock densities and specific heats were obtained experimentally, with 26 samples from the sedimentary layer (mainly sandstone and glutenite from the Cenozoic thermal reservoir) and 79 bedrock samples (mainly dolomite from the carbonate thermal reservoir). As the whole Bohai Bay Basin has a similar stratigraphic distribution (Fig. 2), sedimentary density data were used for the Cenozoic thermal reservoir, and dolomitic bedrock data were used for the carbonate reservoir. For rock heat capacities, the corresponding specific heat values at different temperatures were chosen as reference values for calculation. The final calculation results are reported in Tables 1, 2, and 3. Data formats for the simulation are given in Table 4, which includes the calculations related to different distribution models of input parameters as well as the values of related parameters in different models.

Results

Simulation of the Minghuazhen thermal reservoir

Using Monte Carlo simulation, we calculate the Minghuazhen thermal reservoir as an example. Based on the parameters given in Table 4, the data are obtained from experimental result rather than the simulation. The first step was to define the input parameter values as in Table 4. To solve the parameter uncertainties, different distribution patterns were then assigned. Area was assigned to the

Table 2 Parameters for the Guantaozu thermal reservoir (Chen 1988; Liang et al. 2010; Yan et al. 2001; Zhao et al. 2016)

Tectonic unit	Symbol for geothermal field	Area (km^2)	Thickness (m)	Porosity (%)	Temperature of the thermal reservoir (°C)	Rock density ($kg\ m^{-3}$)	Specific heat of rock ($J\ kg^{-1}$ °C)	Water density ($kg\ m^{-3}$)	Specific heat of water ($J\ kg^{-1}$ °C)
Jizhong depression	A	21,970	200–400 (300)	19–32 (22)	41.5–67.0 (58.5)	2574–2673 (2623)	886–936 (911)	1000	4180
Huanghua depression	B	12,150	130–170 (150)	24–27 (25)	55.5–63.0 (60)	2574–2673 (2623)	848–861 (854)	1000	4180
Linqing depression	C	27,970	50–220 (125)	28–33 (31)	42.0–60.0 (54.0)	2574–2673 (2623)	841–867 (855)	1000	4180
Jiyang depression	D	17,610	70~200 (130)	15–30 (20)	48.5–61.0 (56.0)	2574–2673 (2623)	892–926 (909)	1000	4180
Cangxian uplift	F	5690	100–200 (150)	15–32 (25)	48–65 (52)	2574–2673 (2623)	832–856 (844)	1000	4180
Chengning uplift	G	4323	300–500 (400)	24–36 (30)	45–60 (50)	2574–2673 (2623)	880–924 (902)	1000	4180

Most likely values are provided in parentheses

Table 3 Parameters for the carbonate thermal reservoir (Cheng and Chen 2009; Feng et al. 2013; Tan and Kang 2018; Wu et al. 2011)

Tectonic unit	Number in Fig. 4	Area (km^2)	Thickness (m)	Porosity (%)	Temperature of the thermal reservoir (°C)	Rock density ($kg\ m^{-3}$)	Specific heat of rock ($J\ kg^{-1}$ °C)	Water density ($kg\ m^{-3}$)	Specific heat of water ($J\ kg^{-1}$ °C)
Jizhong depression	1–13	2099	100–500 (250)	0.5–6.04 (2.3)	48–137 (85)	2711–2902 (2806)	841.0–918.8 (879.9)	1000	4180
Huanghua depression	18–24	700	74–260 (163)	0.42–4.4 (3.0)	58–120 (84)	2711–2902 (2806)	869.4–1170 (1019.7)	1000	4180
Linqing depression	25–35	3160	100–350 (220)	0.16–8.37 (4.1)	50–115 (72)	2711–2902 (2806)	836.4–877.1 (856.8)	1000	4180
Jiyang depression	41–46	3955	50–300 (200)	0.8–9.51 (4.8)	55–130 (95)	2711–2902 (2806)	832.2–901.2 (866.7)	1000	4180
Cangxian uplift	14–17	4160	450–750 (620)	1–5.8 (2.4)	55–100 (79)	2711–2902 (2806)	843.4–904.2 (873.8)	1000	4180
Chengning depression	36–40	2410	100–220 (175)	0.5–3 (2.0)	40–105 (65)	2711–2902 (2806)	875.7–1195 (1035.3)	1000	4180
Luzhong uplift	47–49	1020	100–350 (210)	2.84–4.55 (3.75)	50–80 (65)	2711–2902 (2806)	925.0–1062 (993.5)	1000	4180

Most likely values are provided in parentheses

Table 4 Input parameter values for geothermal energy calculations based on Monte Carlo simulation

Parameter	Min value	Most likely value	Max value
Area, A (km^2)	21,970	21,970	21,970
Thickness, H (m)	180	420	620
Porosity, ϕ	30	31	33
Density of rock, ρ_r ($kg\ m^{-3}$)	2574	2623	2673
Specific heat of rock, C_{pr} ($J\ kg^{-1}$ °C)	778	827	876
Density of water, ρ_w ($kg\ m^{-3}$)	1000	1000	1000
Specific heat of water, C_{pw} ($J\ kg^{-1}$ °C)	4180	4180	4180
Temperature of the thermal reservoir, T_R (°C)	31	36	43
Reference temperature, T_S (°C)	15	15	15

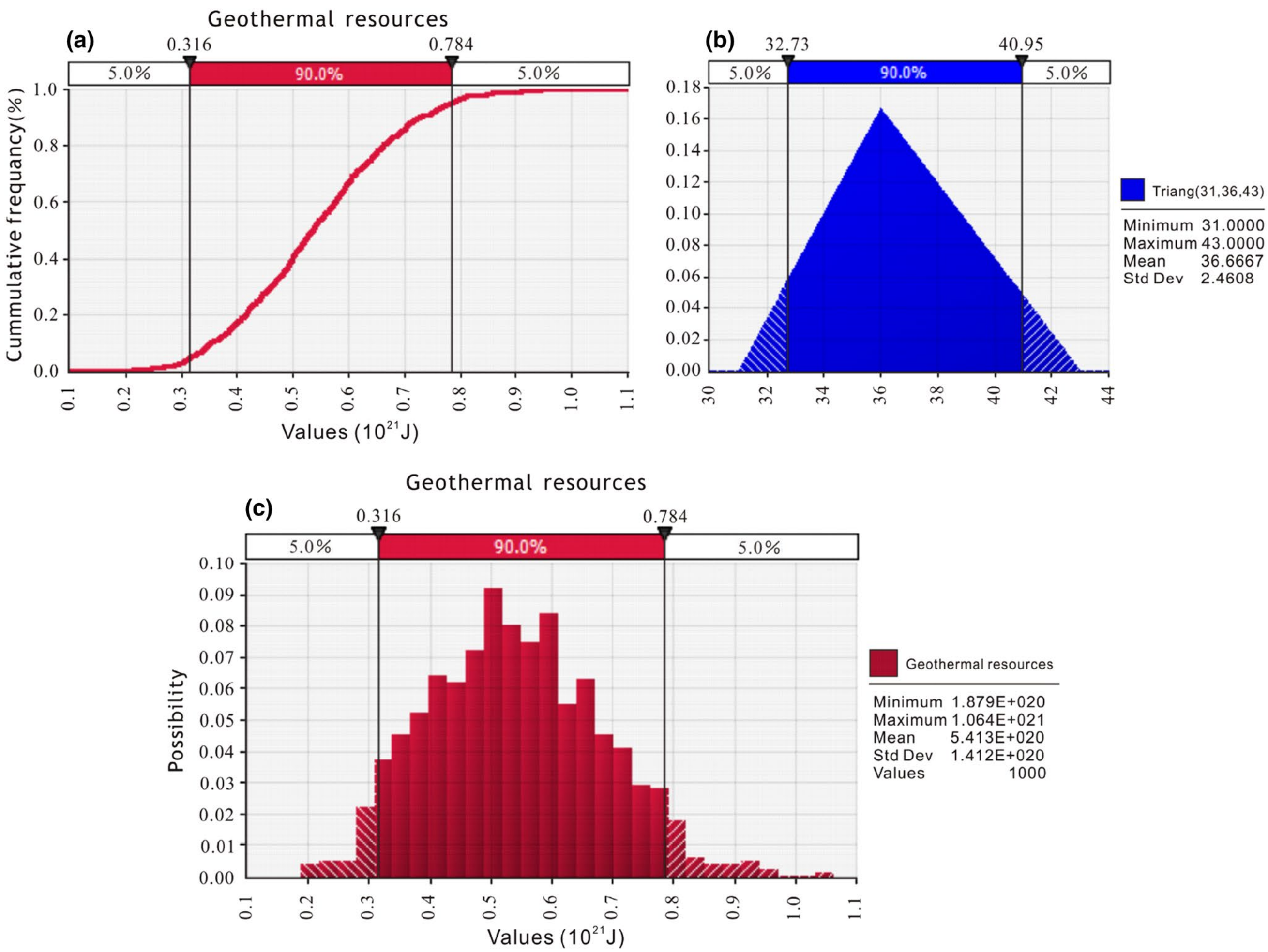

Fig. 7 Simulation results based on Table 4

uniform distribution model, which means that regardless of the number of iterations, the area value is constant as 21,970. Thermal reservoir temperature was assigned to the triangular distribution model, meaning that the analysis would randomly take values from the blue area of Fig. 7b, with each temperature value generating a geothermal resource regardless of the uncertainty of other parameters. Finally, the simulation iteration is set as 1000 times. The results are presented in Fig. 7.

Figure 7c shows the geothermal resources potential in which the value ranges from 0.188×10^{21} J to 1.064×10^{21} J with the mean value of 5.413×10^{20} J. Within this range, the highest probability appears at 5.000×10^{20} J with a probability of > 9% (Fig. 7c). From Fig. 7a, we can get that the probability of geothermal resource potential is above 7.840×10^{20} J or below 3.160×10^{20} J which is less than 5%.

Simulation of the Minghuazhen thermal reservoir

Based on Table 1, we ran the Monte Carlo simulation for the Minghuazhen thermal reservoir. Parameters of area, water density, and specific heat were assigned with the uniform distribution model, and the triangular distribution model was applied to the remaining parameters. The iteration time was 1000 s for each sub-tectonic unit (due to the Minghuazhen thermal reservoir includes six sub-tectonic units in Bohai Bay Basin). Then, we ran the simulation for the sum of the six tectonic units' geothermal potential and the results are shown in Fig. 8.

Figure 8 indicates that the energy potential of the Minghuazhen thermal reservoir is $(1.182–2.283) \times 10^{21}$ J (mean 1.675×10^{21} J), with the highest probability being 1.740×10^{21} J with a probability of >8.5%, and a 90% probability that the geothermal potential is $(1.376–1.990) \times 10^{21}$ J. Dividing the mean value by the reservoir area indicates an energy potential of 1.867×10^{16} J km^{-2}.

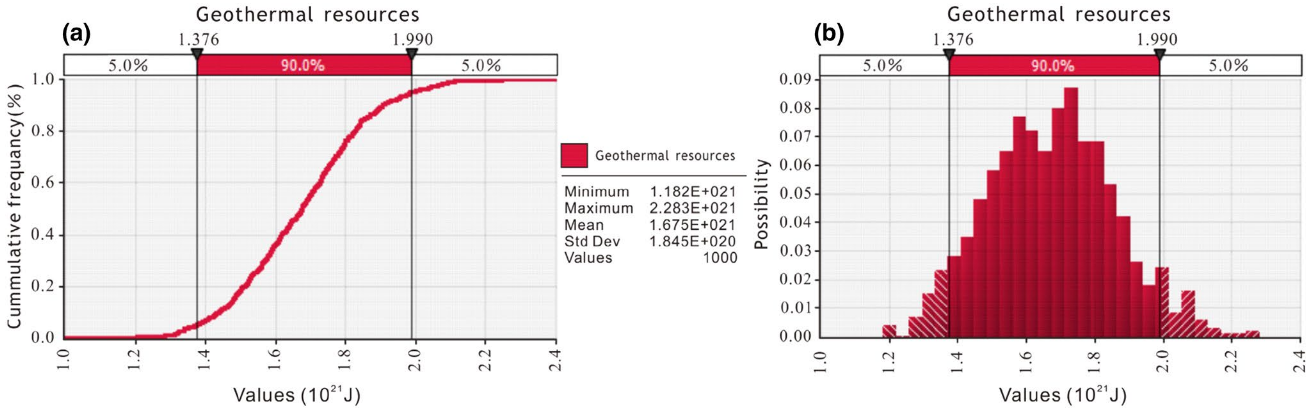

Fig. 8 Simulation results for Minghuazhen thermal reservoir (parameters are given in Table 1)

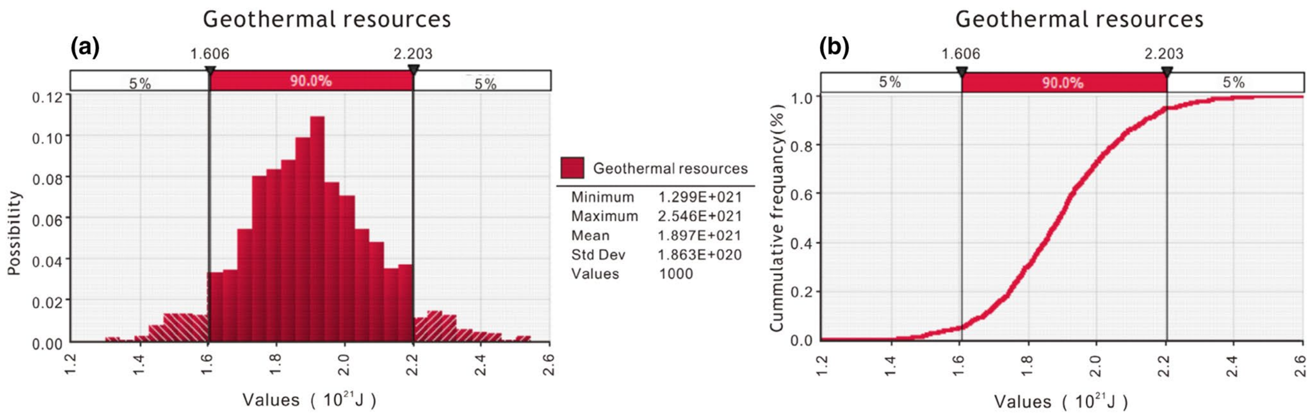

Fig. 9 Simulation results for Guantaozu thermal reservoir (parameters given in Table 2)

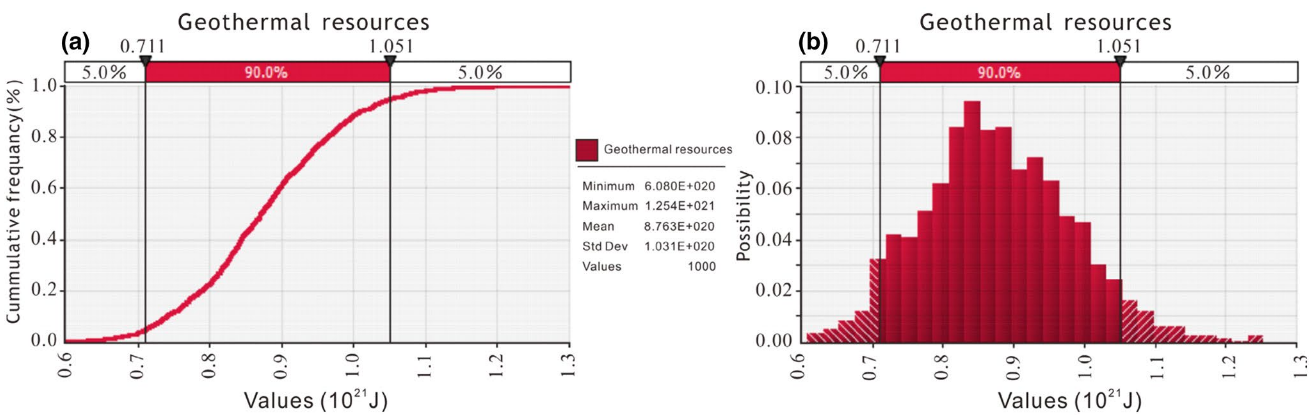

Fig. 10 Simulation results for the carbonate reservoir (parameters given in Table 3)

Simulation of the Guantaozu and carbonate thermal reservoirs

Simulations of the Guantaozu and carbonate reservoirs were run as described in section "Simulation of the Minghuazhen thermal reservoir", with the results being shown in Figs. 9 and 10, respectively. Figure 9 indicates a geothermal resource potential for the Guantaozu reservoir of (1.299–2.546) × 10^{21} J with a mean of 1.897 × 10^{21} J, with 10% probability of the most likely value of 1.937 × 10^{21} J

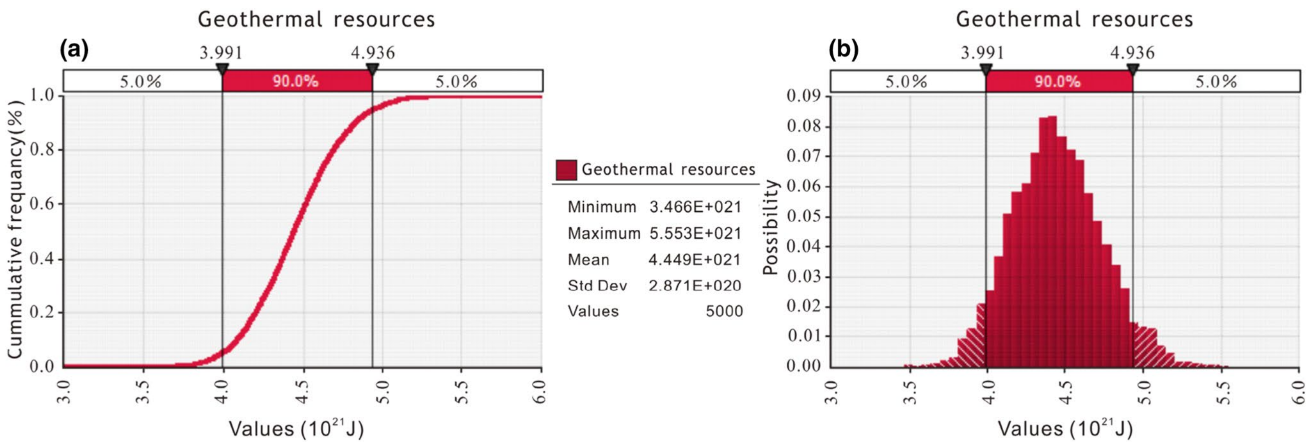

Fig. 11 Geothermal resource simulation results for the sum of the three thermal reservoirs

and a probability of < 5% that the resources are > 2.203 × 10^{21} J or < 1.606 × 10^{21} J (Fig. 9a). Dividing by area indicates a geothermal potential of 2.114 × 10^{16} J km^{-2}.

Figure 10 indicates that the geothermal potential of the carbonate thermal reservoir is (0.608–1.254) × 10^{21} J with a mean of 8.760 × 10^{20} J and a most likely value of 8.450 × 10^{20} J (probability > 9%) and an average geothermal potential of 5.100 × 10^{16} J km^{-2}.

Monte Carlo simulation results for three thermal reservoirs

The total geothermal resources of the above three thermal reservoirs were estimated by running the Monte Carlo simulation for 5000 iterations, with the results being shown in Fig. 11. The simulation gives a resource potential of (3.466–5.553) × 10^{21} J, with a mean of 4.449 × 10^{21} J and a most likely value of 4.400 × 10^{21} J (probability > 8%), and a 90% probability of a range of (3.991–4.936) × 10^{21} J (Fig. 11).

Conclusion

This study used the Monte Carlo method to simulate probability distributions of geothermal resources in Bohai Bay Basin and to quantify resource capacities. Geothermal resources within the three thermal reservoirs in Bohai Bay Basin total (3.466–5.553) × 10^{21} J, with a mean of 4.449 × 10^{21} J and a most likely value of 4.400 × 10^{21} J, which is equivalent to 1500 × 10^{8} tons of standard coal heat content. The most promising carbonate thermal reservoir has an average geothermal resource potential of 5.100 × 10^{16} J km^{-2}, twice that of the corresponding Cenozoic reservoir. However, the total geothermal resource within the carbonate thermal reservoir is relatively small compared with the total in the Cenozoic thermal reservoirs, because only the currently discovered carbonate fields were assessed. Considering the extensive development of carbonate strata within Bohai Bay Basin, the total geothermal energy stored in the carbonate reservoir is likely to be much greater than this simulated value. The abundant geothermal resources of Bohai Bay Basin may alleviate energy shortages and improve environmental conditions, particularly with respect to reducing smog problems caused by the burning of fossil fuels in the Beijing–Tianjin–Hebei region and help to build the green cities in Xiong'an New District.

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Compliance with ethical standards

Conflict of interest None.

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