Research Article

Zoning of development and utilization and evaluation of deep geothermal resources in Xiong'an New Area

Ming-xiao Yu[1,2], Xi Zhu[1,2*], Gui-ling Wang[1,2], Wei Zhang[1,2], Feng Ma[1,2]

[1] *Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, Shijiazhuang*, 050061, *China.*
[2] *Technology Innovation Center for Geothermal & Hot Dry Rock Exploration and Development, Ministry of Natural Resources, Shijiazhuang* 050061, *China.*

Abstract: Xiong'an New Area boasts abundant geothermal resources, with widespread Jixianian geothermal reservoirs serving as key targets for exploration and development. Zoning geothermal resources helps characterize their distribution and attributes, offering critical guidance for their sustainable exploitation and utilization. This study integrates data from drilling and production tests across 21 geothermal wells to analyze the Jixianian strata, including depth, thickness, temperature, single-well water yield, Groundwater Level Depth (GWD), and Total Dissolved Solids (TDS). Employing fuzzy mathematics, a zoning analysis was performed, yielding quantitative evaluation scores and delineating favorable zones for development. Key findings include: (1) Geothermal reservoirs in the Rongcheng and Niutuozhen uplifts exhibit shallow burial depths, substantial thicknesses, high productivity, and relatively low temperatures, making them highly suitable for large-scale geothermal exploitation; (2) Zones with high resource potential but uncertain conditions require further exploration to mitigate development risks; (3) Areas near the Rongcheng fault or Jixianian strata buried deeper than 4,000 m are recommended for deferred exploitation; (4) Comprehensive evaluation reveals that the Jixianian carbonate geothermal reservoirs in Xiong'an New Area manifest geothermal resources of $5,370.31 \times 10^{16}$ J, geothermal fluid reserves of 101.17×10^8 m^3, and recoverable fluid reserves of 93.41×10^4 m^3/d under balanced extraction and reinjection. Recoverable geothermal heat amounts to 9.36×10^{16} J/a, equivalent to 319.4×10^4 t/a of standard coal. This study provides valuable insights into the exploration and sustainable exploitation of deep geothermal reservoirs in Xiong'an New Area, enhancing resource utilization and contributing to the development of a green and sustainable Xiong'an New Area.

Keywords: Zoning of geothermal resources; Fuzzy mathematics; Geothermal energy; Extraction and reinjection balance; Jixianian geothermal reservoirs

Introduction

Energy serves as the foundation and driving force of human civilization's advancement. Currently, China's energy structure is dominated by fossil

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fuels, which, while indispensable, pose significant environmental challenges. As a result, it is urgent to identify viable pathways for developing low-carbon and sustainable energy sources.

Geothermal energy, as a green, low-carbon, and renewable resource, offers numerous advantages, including recyclability, controllable extraction, and a stable, continuous energy supply (Wang et al. 2020; Wei et al. 2022; Liu et al. 2023; Sun et al. 2023). According to statistical estimates, China's annual recoverable hydrothermal resources are equivalent to 18.65×10^8 tons of standard coal, highlighting its sustainable potential for development and utilization (Wang et al. 2017). However, the current rate of exploration and utilization

remains relatively low. In 2020, geothermal energy consumption constituted only 0.6% of China's total energy usage (Wang et al. 2020). Amid accelerating demands for energy and the push for green, low-carbon transformation, there is an increasing imperative to intensify efforts in the exploration, exploitation, and research of geothermal resources (Lund et al. 2021).

In recent years, significant progress has been made in zoning research aimed at facilitating the efficient and optimal exploration, exploitation, and utilization of geothermal resources. For instance, Shang et al. (2012) investigated moderate- to low-temperature geothermal resources in northern Ji'nan. By analyzing geothermal gradients, geological structural conditions, and geothermal reservoir types, they classified the study area into four zones: Top priority, priority, secondary priority, and general geothermal exploitation zones, while providing corresponding recommendations for resource exploitation and utilization. Based on extensive datasets, Siler et al. (2017) and Lindsey et al. (2018) applied the play fairway analysis-a methodology initially developed for predicting hydrocarbon reservoir distributions in petroleum exploration – to geothermal studies. This approach allowed them to predict the distribution of favorable geothermal zones and assess their exploitability comprehensively.

Similarly, Liu et al. (2018) conducted a zoning study of geothermal resource potential in Beijing. Their analysis employed three key indicators, i.e. the degree of geothermal fluid exploitation, the heat potential modulus of geothermal fluids, and the maximum water level decline rate. Based on these criteria, they categorized Beijing's geothermal fields into six zones for evaluation: Severely overexploited zone, overexploited zone, generally equilibrium zone, zone with certain exploitation potential, zone with exploitation potential, and zone with high exploitation potential. Further advancing the field, Wang et al. (2019) used geochemical data from the Beijing-Tianjin-Hebei region to analyze the distributions of geochemical anomaly combinations of indicator elements. By integrating these findings with regional geological data, they delineated geothermal prospect zones and demonstrated a strong correlation between these zones and the distributions of deep faults as well as Yanshanian intermediate-mafic magmatic rocks. These zoning studies have provided invaluable insights, offering effective support for the planning, exploitation, and sustainable utilization of geothermal resources.

Xiong'an New Area features a typical paleo-

buried hill-type complex hydrothermal system within a sedimentary basin. Its distinctive and representative geothermal resource conditions establish it as one of the most promising regions for hydrothermal resource exploitation and utilization in the east-central part of China (Kong et al. 2017; Zhang et al. 2019; Wang et al. 2020). Extensive studies on the area's regional structural geology, temperature field, and geothermal resource formation mechanism has laid a solid research foundation for geothermal studies.

Utilizing comprehensive field data from the North China region, Chen et al. (1988) described the characteristics and distributions of the regional geothermal field, delineated local geothermal anomaly zones, and proposed an accumulation model for geothermal resources in the North China Basin. This work has provided fundamental data for subsequent geothermal research in the region. Wu et al. (2018), Wang et al. (2020) and Wang et al. (2021) investigated the key parameters of karstic geothermal reservoirs within the Jixianian Wumishan Formation through the development of high-yield geothermal wells in Xiong'an New Area. Their work confirmed the significant potential for geothermal exploitation in the deeper regions of the area. Utilizing temperature measurement data obtained from drilling operations and thermal conductivity test results of rock samples, Chang et al. (2016) and Wang et al. (2019) analyzed the characteristics of the current geothermal field, offering fundamental data for simulating the deep thermal structure and temperature field in the area. Further insights into geothermal fluid were provided by Liu et al. (2020), Zhu et al. (2022), and Yu et al. (2022), who examined the hydrochemical and isotopic properties of fluids from different geothermal reservoirs in Xiong'an New Area. Their research identified distinct hydrochemical types and applied isotopic theory to explore the genetic mechanisms of geothermal fluid information.

Overall, the aforementioned research has provided valuable insights, significantly informing the exploitation and utilization of geothermal resources in Xiong'an New Area. However, in alignment with the goals of developing a clean, low-carbon, safe, and efficient energy system and achieving carbon peak and neutrality targets, the need for intensified exploitation of deep geothermal resources has become increasingly pressing. Effectively and scientifically exploiting and utilizing geothermal resources across distinct zones and identifying innovative exploitation and utilization models now pose new challenges for geothermal research and development. Previous zoning efforts

for exploitation and utilization suitability in Xiong'an New Area were limited to the existing boundaries of geothermal fields, resulting in indistinct zoning outcomes, thus failing to adequately reflect the regional characteristics of geothermal resources necessary for effective exploitation and utilization.

Building on the comprehensive geothermal exploration conducted by the China Geological Survey, this study analyzed survey and completion reports, geophysical exploration data, relevant drawings from existing geothermal wells, as well as pumping and reinjection test data from representative geothermal wells in Xiong'an New Area. By moving beyond the constraints of previous geothermal field boundaries, this study thoroughly examined the spatial distributions and characteristics of geothermal reservoirs in the Jixianian Wumishan and Gaoyuzhuang formations, the primary targets for geothermal resource development and utilization in the region.

This research established zoning requirements and criteria for characterizing and investigating geothermal resource potential across the entire area. The findings offer essential theoretical and practical guidance for deep geothermal reservoir exploration and exploitation in Xiong'an New Area. They also support the identification of promising resource targets, foster the optimized utilization of geothermal energy, and contribute to the development of a green, sustainable Xiong'an.

1 Geological setting of the study area

Xiong'an New Area is strategically located in the hinterland of Beijing, Tianjin, and Baoding, Encompassing Xiong County, Rongcheng, and Anxin counties under the jurisdiction of Baoding City, Hebei Province, as well as Qijianfang Township of Renqiu County, Maozhou Town, Gougezhuang Town, and Longhua Township of Gaoyang County (Cui et al. 2022; Fig. 1c). In terms of regional structural geology, Xiong'an New Area is located within the Jizhong Depression, situated in the western portion of the Bohai Bay Basin. The area hosts fourth-order tectonic units, including the Langfang Sag, Rongcheng Uplift, Niutuozhen Uplift, Baoding Sag, Gaoyang Low Uplift, Raoyang Sag, and Baxian Sag (Regional Geology of China, Hebei Province, 2017). During the Sinian period, the region was characterized by a peneplain with minimal folding, faulting, and magmatic activity, and overall uplifting and subsiding crust. Following the Indosinian movement, the region transitioned to a continental-margin active zone. During the Yanshanian period, the area experienced significant folding and faulting, accompanied by extensive volcanic eruptions and granite magma intrusions. These events induced substantial transformations in the tectonic framework, leading to the development of numerous NNE- and NE-trending secondary structures with alternating uplifts and depressions within the Sino-Korean
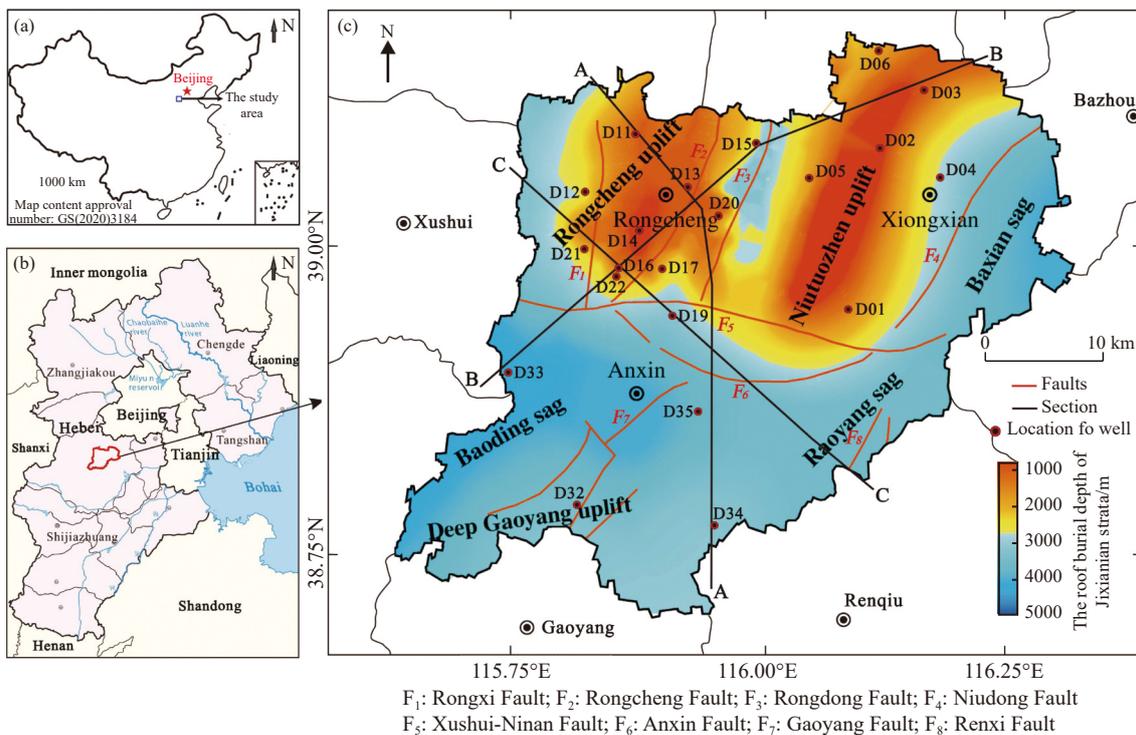

F₁: Rongxi Fault; F₂: Rongcheng Fault; F₃: Rongdong Fault; F₄: Niudong Fault
F₅: Xushui-Ninan Fault; F₆: Anxin Fault; F₇: Gaoyang Fault; F₈: Renxi Fault

Fig. 1 The location and geological conditions of Xiong′an New Area (Zhu et al. 2023)

paraplatform. The presence of deep tensional faults further shaped the region's geological structure (Zhu et al. 2023). After the Neogene, the Himalayan movement led to widespread subsidence, creating a unified sedimentary basin. By the Quaternary, the Neogene and Quaternary formations were unconformably deposited over the strata. The cumulative impact of multiple tectonic movements has resulted in the current geological fracework of Xiong'an New Area, characterized by Cenozoic cap rocks and alternating convex and concave bedrock structures.

Xiong'an New Area encompasses the Archean metamorphic rock, Upper-Middle Proterozoic carbonate rock, Ordovician-Cambrian, Neogene sandstone, and Quaternary sediment from bottom to top (Xing et al. 2022). Among these, the primary deep geothermal reservoirs targeted for exploitation and utilization are carbonate formations. These reservoirs are widely distributed throughout the area and consist of various dolomite types, including finely crystalline, calcareous, and argillaceous dolomites. The carbonate reservoirs in Xiong'an New Area are characterized by extensive spatial distributions, elevated temperatures, and high reservoir quality. Over prolonged geological periods, these carbonate formations have undergone denudation, weathering, and leaching, resulting in well-developed dissolution pores and fractures. These structural features provided highly favorable storage spaces, particularly in advantageous structural positions (Yu et al. 2023). Currently, the Jixianian Wumishan Formation serves as the primary reservoir for geothermal exploitation and utilization in Xiong'an New Area. Geothermal exploration wells have also identified significant potential within the Gaoyuzhuang Formation, suggesting its viability as a promising geothermal reservoirs for future development and exploitation.

2 Geological characteristics of geothermal resources

Xiong'an New Area features well-developed fault structures and karst systems, facilitating the deep circulation of groundwater. As groundwater moves through the carbonate strata, it undergoes convective heating, allowing deep heat to migrate more efficiently to shallow layers. This dynamic process results in localized thermal anomalies, making the region rich in geothermal resources.

The fault network in Xiong'an New Area is predominantly NE-trending and includes txtensional faults such as the Rongcheng, Rongdong, and Niudong faults, as well as the NWW-trending

faults like the Xushui-Anxin and Niunan faults. These faults exert significant control over the distribution of secondary tectonic units and the formation of geothermal resources. The Rongcheng fault, extending down to the crystalline basement, acts as a growth fault, regulating the development of the Neogene strata (Zhao et al. 2020). The Rongdong fault represents the boundary between the Niutuozhen and Rongcheng uplifts. The Niudong fault, a permanently active deep fault interscting the crystalline basement, controlling the development of the Niutuozhen Uplift and the Baxian Sag (Zhu et al. 2023) (Profiles A and B in Fig. 2). The Xushui fault is a deep boundary fault between the Rongcheng Uplift and the Baoding Sag (Profile C in Fig. 2). The Niunan fault is a normal fault marking the southwestern boundary of the Niutuozhen Uplift, with permanent activity breaking through the basement (Profile C in Fig. 2). The Gaoyang fault influences the thickness and structural configuration of the Paleogene strata. These faults play a dual role as structural boundaries and as conduits for heat and fluid flow, thereby significantly contributing to the formation and distribution of geothermal resources. Additionally, the carbonate reservoirs, serving as the primary deep reservoirs for exploitation and utilization, exhibit highly developed rock fissures and excellent thermophysical properties. These characteristics are essential for the superior geothermal resources in Xiong'an New Area. Overall, the area's intricate fault structures promote the deep circulation of groundwater, allowing it to flow along these faults for convection heating. This process is further enhanced by efficient groundwater movement and water-rock heat exchange. Together with favorable geological and hydrogeological conditions, these mechanisms contribute to the significant accumulation of deep geothermal resources within the carbonate strata, particularly in areas featuring extensively developed karst fissures.

3 Zoning and potential evaluation of deep geothermal resources

3.1 Zoning evaluation indicator system of geothermal resources and characteristics revealed by single-factor diagrams

This study employed a comprehensive analysis of drilling, logging, and production test data from 21 geothermal wells, as well as seismic and other
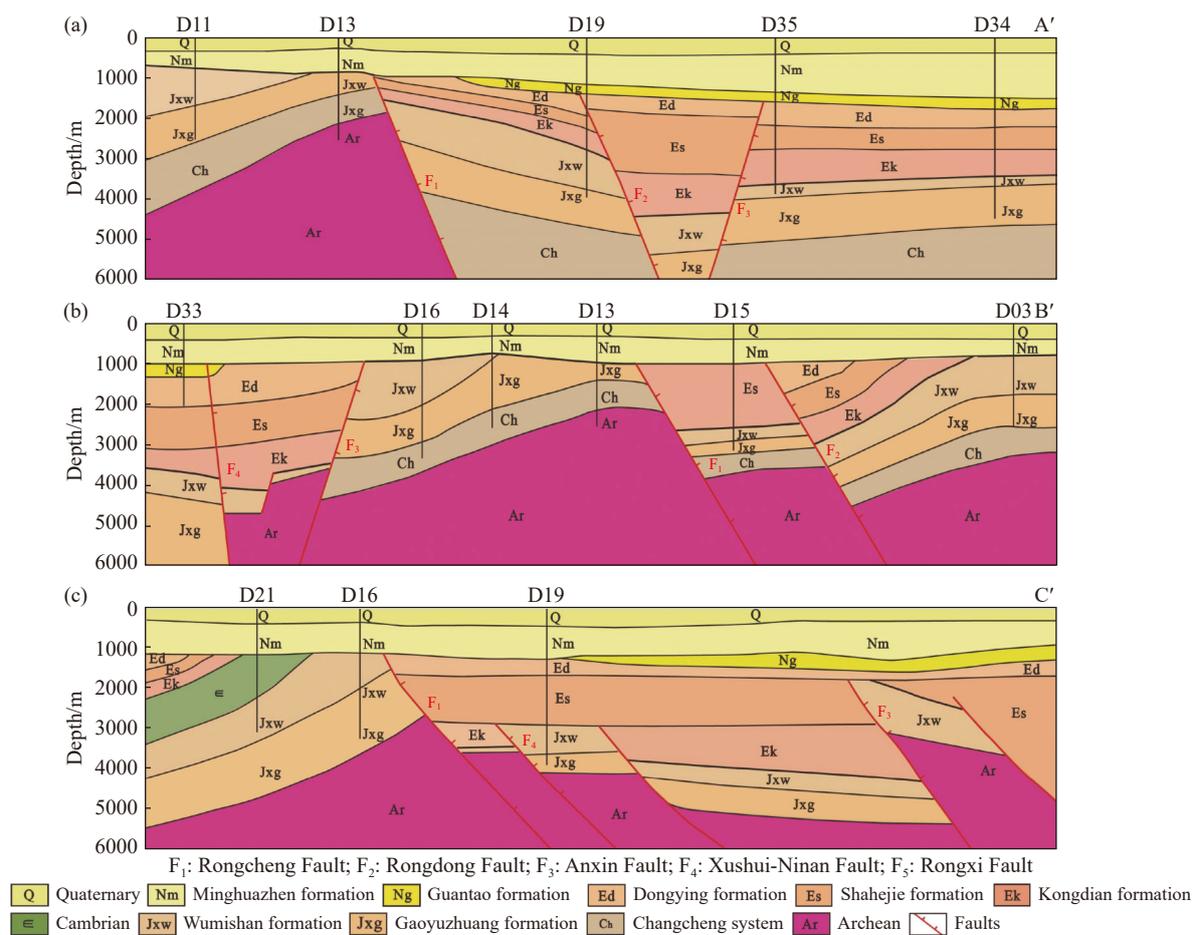
Fig. 2 Geological profile of the study area

geophysical exploration data. To characterize and assess the exploitation and utilization conditions of Jixianian geothermal resources, six key evaluation factors were selected as zoning indicators: the roof burial depth and thickness of Jixianian strata, the central temperature, single-well water yield, and GWD of Jixianian geothermal reservoirs, and the TDS content of geothermal fluids in Jixianian geothermal reservoirs. These factors were used to study the spatial distributions and characteristics of Jixianian geothermal reservoirs across the area. Based on the distribution and data characteristics revealed by diagrams of various evaluation factor, this study determined the grades and step lengths for the evaluation factors: (1) the roof burial depth of Jixianian strata ranges between 500 m and 4,500 m, with a step length of 500 m; (2) the thickness of Jixianian strata ranges between 600 m and 1,600 m, with a step length of 200 m; (3) the central temperature of Jixianian geothermal reservoirs ranges between 50°C and 110°C, with a step length of 10°C; (4) the GWD of Jixianian geothermal reservoirs ranges between 85 m and 125 m, with a step length of 5 m; (5) the single-well water yield of Jixianian geothermal reservoirs ranges between

30 m³/h and 150 m³/h, with a step length of 10 m³/h; (6) the TDS content of geothermal fluids in Jixianian geothermal reservoirs ranges between 2,300–2,900 mg/L, with a step length of 100 mg/L (Fig. 3).

3.2 Zoning evaluation methods for the exploitation and utilization of geothermal resources

The zoning of exploitation and utilization suitability of geothermal resources in Xiong'an New Area was conducted using fuzzy mathematics, employing methods such as the Analytic Hierarchy Process (AHP), the expert scoring method, and the fuzzy comprehensive evaluation method (Pei et al. 2023). Flowchart of the research process is shown in Fig. 4, consisting the following steps:

(1) The evaluation for the zoning of exploitation and utilization suitability of deep geothermal resources in Xiong'an New Area. Among the six key indicators, the most significant one is single-well water yield, which directly influences the exploitation and utilization of geothermal energy.
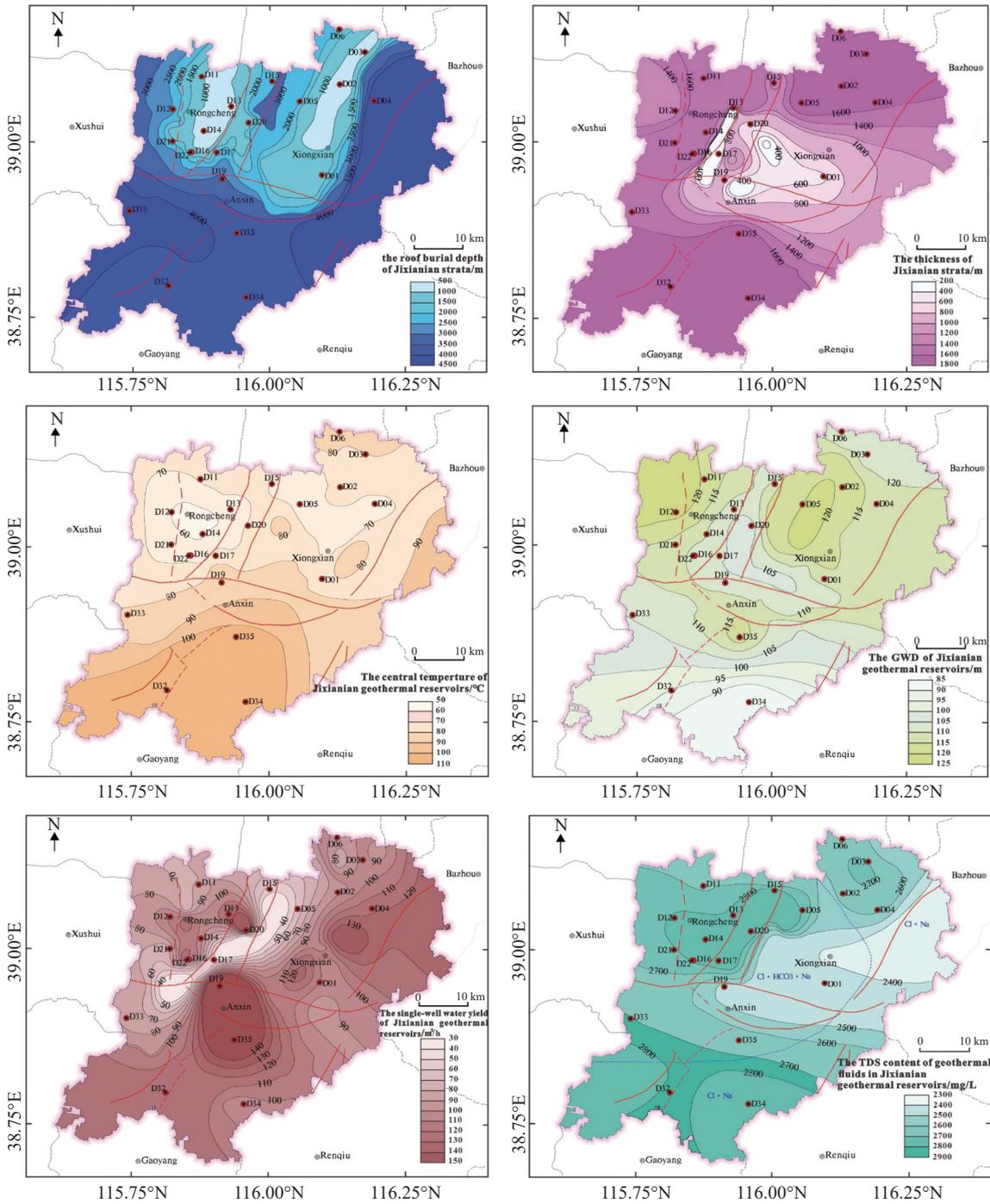
Fig. 3 Evaluation index map of geothermal resources zoning in Xiong′an New Area

The second is the central temperature of the geothermal reservoirs, as it determines the economic benefits of geothermal utilization projects. Roof burial depth and the GWD rank the third and the fourth, which impact the exploitation cost of geothermal resources. The formation thickness plays a crucial role in heat conservation within geothermal reservoirs. TDS content of geothermal fluids primarily affects the exploitation of geothermal fluids, showing the lowest significance. According to the above analysis, this study estab-

lished an evaluation indicator dataset for assessing the exploitation and utilization suitability of deep geothermal resources in Xiong'an New Area. The indicators were prioritized according to their relative significance (Table 1). The sequence of their significance is as follows: Single-well water yield of Jixianian geothermal reservoirs > central temperature of Jixianian geothermal reservoirs > roof burial depth of Jixianian strata > GWD of Jixianian geothermal reservoirs > thickness of Jixianian strata > TDS content of geothermal fluids in
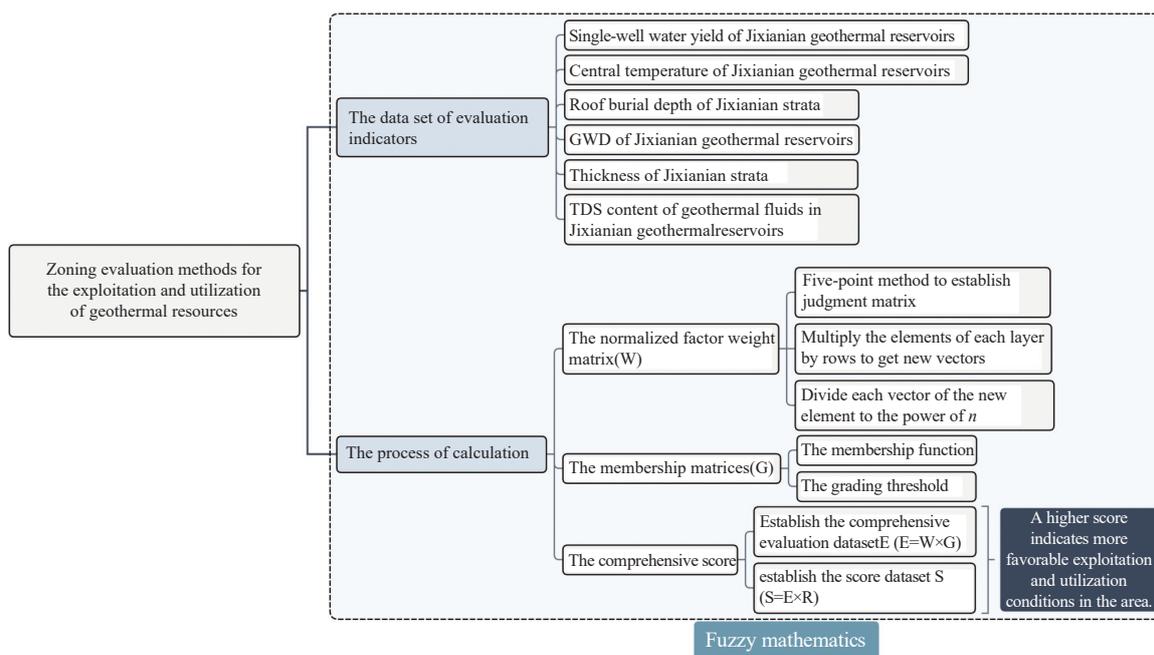
Fig. 4 Flowchart of the research

Table 1 The data set of selected evaluation indicators

The data set of evaluation indicators	
C_1	Single-well water yield of Jixianian geothermal reservoirs (m^3/h)
C_2	Central temperature of Jixianian geothermal reservoirs (°C)
C_3	Roof burial depth of Jixianian strata (m)
C_4	Groundwater level depth of Jixianian geothermal reservoirs (m)
C_5	Thickness of Jixianian strata (m)
C_6	TDS content of geothermal fluids in in Jixianian geothermal reservoirs (mg/L)

Jixianian geothermal reservoirs.

(2) Based on the evaluation indicator dataset, a judgement matrix of indicators $A=(a_{ij})_{mn}$ ($a_{ij}>0$; $a_{ji}=1/a_{ij}$; $a_{ii}=1$) was established using the AHP. The five-point scale method was employed to assign values reflecting the relative importance of each indicator pair. A higher scale value suggests that the former indicator is more significant than the latter one (Pang et al. 2020). Specifically, the scale value 1 indicates equal significance between two indicators, whereas the maximum scale value 5 signifies extreme dominance of the former indicator over the latter. For instance, the scale value 5 for C_3 and C_5 indicates that the roof burial depth of Jixianian strata is extremely significant compared to the thickness of Jixianian strata. The scale value 2 for C_1 and C_2 as well as C_1 and C_3 implies that relative to the single-well water yield of Jixianian geothermal reservoirs, the central temperature of Jixianian geothermal reservoirs and the roof burial depth of Jixianian strata are equally significant, the judgment matrix of this study is shown in Table 2.

The element of each layer were multiplied by

rows to get new vectors. After this, each vector element was divided by the power of n to obtain M_i, which was then normalized to get the corresponding eigenvectors of the judgement matrix using $W_i=M_i/\sum_{i=1}^{n}M_i$. This weight matrix passed the consistency check, yielding $W_{1×n}$ of the zoning evaluation indicator system for the exploitation and utilization suitability of deep geothermal resources, namely $W_{1×6}$ = [0.2677, 0.2551, 0.2313, 0.1116, 0.0796, 0.0546]. Values in this weight matrix represent the weights of corresponding zoning evaluation indicators for exploitation and utilization suitability. For example, the weight values 0.2677 and 0.2313 were assigned to the single-well water yield of Jixianian geothermal reservoirs and the roof burial depth of Jixianian strata, respectively.

(3) The indicators for evaluating the exploitation and utilization suitability of deep geothermal resources were classified into five levels: Excellent, good, moderate, poor, and very poor. Based on the distribution characteristics of these indicators in Xiong'an New Area, the grading levels for

Table 2 Index weighted evaluation matrix

Evaluation indicators	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1	2	2	3	3	4
C_2	1/2	1	3	3	4	2
C_3	1/2	1/2	1	4	5	4
C_4	1/2	1/3	1/4	1	2	3
C_5	1/2	1/3	1/5	1/2	1	2
C_6	1/3	1/4	1/4	1/3	1/2	1

each indicator at corresponding locations were determined. To highlight the potential for exploiting and utilizing geothermal resources, this study established a zoning evaluation grade table for the suitability of deep geothermal resources in Xiong'an New Area (Table 3). Membership matrices G (Equation 2) were created using the membership function and the grading threshold (Equation 1). Xiong'an New Area and its surrounding areas were divided into 1941 grids using the ArcGis10.7 software. According to Equation 1, values for all metrics at each grid point were assigned, resulting in 1941 membership matrices $G_{6\times5}$.

$$\mu_1(x)\begin{cases} 1\,(x \leqslant a_1) \\ \dfrac{a_2-x}{a_2-a_1}\,(a_1 < x < a_2) \\ 0\,(x \geqslant a_2) \end{cases}$$

$$\mu_1(x)\begin{cases} 0\,(x \leqslant a_{j-1}, x \geqslant a_{j+1}) \\ \dfrac{x-a_{j-1}}{a_j-a_{j-1}}\,(a_{j-1} < x < a_j) \\ \dfrac{a_{j+1}-x}{a_{j+1}-a_j}\,(a_j < x < a_{j+1}) \end{cases}$$

$$\mu_1(x)\begin{cases} 0\,(x \leqslant a_{m-1}) \\ \dfrac{x-a_{m-1}}{a_m-a_{m-1}}\,(a_{m-1} < x < a_m) \\ 1\,(x \geqslant a_m) \end{cases} \quad (1)$$

Where: x denotes the actual value of an indicator, and a_1, a_{j-1}, a_j, and a_{j+1} stands for the values repre-

sented by grades R_1, R_{j-1}, R_j, and R_{j+1}, respectively. Membership matrix G is expressed as follows:

$$G=\begin{bmatrix} G_1 \\ G_2 \\ \vdots \\ \vdots \\ G_n \end{bmatrix}=\begin{bmatrix} g_{11}g_{12} & \cdots & g_{1j} & \cdots & g_{1m} \\ g_{21}g_{22} & \cdots & g_{2j} & \cdots & g_{2m} \\ \vdots\vdots & \ddots & \vdots & & \vdots \\ g_{n1}g_{n2} & \cdots & g_{nj} & \cdots & g_{nm} \end{bmatrix}_{n\times m} \quad (2)$$

Where: g_{ij} represents the membership degree of indicator C_i corresponding to R_j.

(4) Through fuzzy arithmetic, a comprehensive evaluation dataset E was derived by multiplying the weight matrix W by the membership matrix G (Equation 3). Subsequently, the multiplication of the comprehensive evaluation dataset E with the scoring matrix R ($R = [10, 8, 6, 4, 2]'$) yielded the score dataset S, denoted as $S=E.R$. This score dataset reflects the grading threshold values of corresponding zones, where a higher score indicates more favorable exploitation and utilization conditions in the area.

$$\begin{bmatrix} w_1,w_2,\cdots,w_i,\cdots,w_n \end{bmatrix} *$$
$$\begin{bmatrix} g_{11}g_{12} & \cdots & g_{1j} & \cdots & g_{1m} \\ g_{21}g_{22} & \cdots & g_{2j} & \cdots & g_{2m} \\ \vdots\vdots & \ddots & \vdots & & \vdots \\ g_{n1}g_{n2} & \cdots & g_{nj} & \cdots & g_{nm} \end{bmatrix}_{n\times m} =$$
$$[e_1,e_2,\cdots,e_i,\cdots,e_m] \quad (3)$$

Where: e_j represents the probability that the corresponding zone is rated as level R_j considering all indicators.

3.3 Zoning results for the exploitation and utilization of deep geothermal resources

By applying fuzzy mathematics, this study determined the quantitative evaluation scores and

Table 3 Index weighted evaluation matrix

Evaluation indicators	Grade				
	R1 (excellent)	R2 (good)	R3 (moderate)	R4 (poor)	R5 (very poor)
C_1 Single-well water yield of Jixianian geothermal reservoirs (m³/h)	120	100	80	60	40
C_2 Central temperature of Jixianian geothermal reservoirs (°C)	100	80	60	40	20
C_3 Roof burial depth of Jixianian strata (m)	500	1,500	2,500	3,500	4,500
C_4 Groundwater level depth of Jixianian geothermal reservoirs (m)	85	95	105	115	125
C_5 Thickness of Jixianian strata (m)	1,600	1,300	1,000	700	400
C_6 TDS content of geothermal fluids in Jixianian geothermal reservoirs (mg/L)	2,100	2,300	2,500	2,700	2,900

spatial distributions of favorable zones for deep geothermal resources in Xiong'an New Area. As shown in the Fig. 5, zones with scores ≥6.8 were identified as highly favorable for deep geothermal resource exploitation. In terms of geothermal indicators, these zones are characterized by high single-well water yield, shallow burial depths of geothermal reservoirs, and relatively small formation thicknesses. In other cases, favorable zones exhibit moderate single-well yield, moderate burial depths of geothermal reservoirs, and relatively large formation thicknesses. The favorable zones are primarily distributed in a NE-directed zonal pattern along the periphery of Rongcheng and Xiong County. Starting from the boundary of Xiong'an New Area between northern Rongcheng County and Jiaguang Township, these zones extend southward to Santai Town of Anxin County, westward to Xiaoli Town, and eastward to Bayu Township. In the Xiong County area, they extend westward to Zhugezhuang Township, eastward to Xiong County, southward to northern Baiyangdian, and northward to Beishakou Township. Tectonically, these zones are located at the top of the Rongcheng and Niutuozhen uplifts, making them highly suitable for large-scale geothermal exploitation. The recommended drilling depths range from 1,500 m to 2,500 m. Geothermal resources in these zones are primarily utilized for urban heating, as well as for agriculture activities such as planting and breeding in rural areas.

Zones with comprehensive scores ranging from 5.6–6.8 exhibit relatively high single-well water yield, deep burial depths of geothermal reservoirs, and small formation thicknesses. Alternatively, they may display moderate single-well water yield, shallow burial depths, and moderate formation thicknesses. These zones are primarily situated along the periphery of Rongcheng and Xiong County, as well as southern Anxin County. Specifically, they are distributed across Xiaoli Town, Dahe Town, and Pingwang Township of Rongcheng County, and around Santai Town of Anxin County. In the Xiong County area, these zones extend westward to the eastern Xiong County, eastward to Longwan Town, southward to the southern Gaoyang Low Uplift, and northward to northwestern Mijiawu Township. These zones are relatively suitable for large-scale exploitation of deep geothermal resources, with recommended drilling depths ranging from 2,000–3,000 m for the Rongcheng and Niutuozhen uplift zones, and 3,000–4,500 m for trough areas surrounding the uplifts and the Gaoyang geothermal field. Geothermal resources in these areas are primarily utilized for urban heating and for planting and breeding purposes near rural towns. Despite the deep burial depths, geothermal resources in southern Anxin County exhibit temperatures exceeding 100°C, enabling cascade utilization, including power generation, heating, and agriculture applications such as planting and breeding in rural towns.

Zones with comprehensive scores ranging from 4.4–5.6 exhibit relatively low single-well water yield, moderate burial depths, and moderate formation thicknesses. Alternatively, they may display moderate single-well water yield, deep burial depths, and moderate formation thicknesses. These
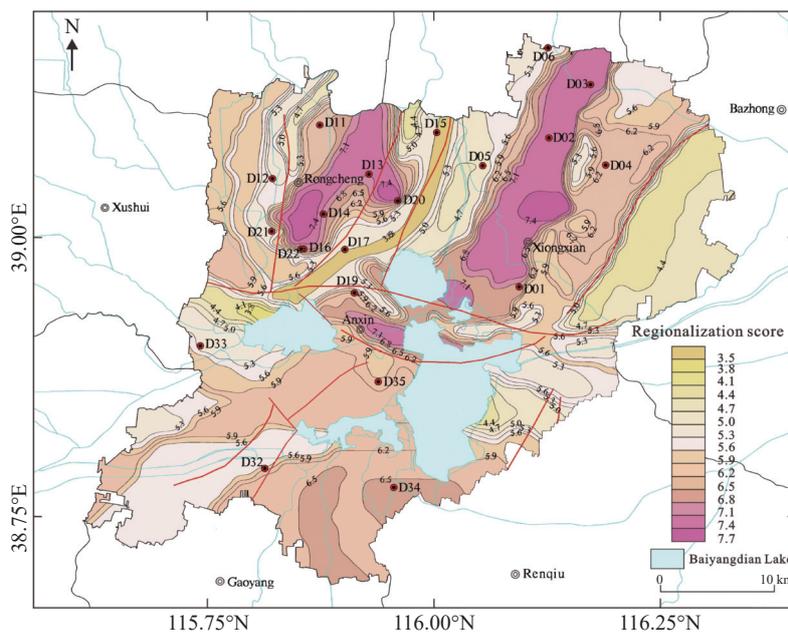

Fig. 5 The regionalization score of Xiong′an New Area

zones are primarily distributed across western and eastern Rongcheng County, eastern and southern Xiong County, and the surrounding areas of Anxin County. Tectonically, these zones are located in the western slope zone and eastern trough area of the Rongcheng Uplift, as well as the southwestern Gaoyang Low Uplift. Apart from a few zones near uplifts, the Jixianian strata generally have deep roof burial depths, mostly exceeding 3,000 m, with significantly varying thicknesses and temperatures. Additionally, zones with shallower burial depths tend to exhibit low productivity.

Zones with comprehensive scores ranging from 3.5–4.4 display relatively low single-well water yield, deep burial depths, and small formation thicknesses. These areas are primarily distributed in southwestern Rongcheng County, southeastern Anxin County, and eastern Xiong County. Tectonically, they are located within the eastern trough area of the Rongcheng Uplift, the transition zone between the Niutuozhen Uplift and the Bazhou Sag, the Bazhou Sag itself, and the northwestern Gaoyang Low Uplift. These zones are characterized by relatively low levels of exploitation. Zones with comprehensive scores of ≤3.5, influenced by the Rongcheng fault, feature Archean gneiss intrusions into Jixianian strata near the fault, leading to highly variable formation thicknesses. Exploration wells in these areas have revealed low productivity, and exploitation is therefore not recommended.

3.4 Potential evaluation of deep geothermal resources

Accurately evaluating geothermal resources is essential for achieving the sustainable exploitation and utilization of geothermal resources in Xiong'an New Area and advancing carbon neutrality (Zhu et al. 2023). Following the *Specification for Estimation and Evaluation of Geothermal Resources* (DZ/T 0331—2020) issued by the Ministry of Natural Resources, this study employed the reservoir evaluation method and the extraction and reinjection balance method to evaluate the geothermal potential of Jixianian geothermal carbonate reservoirs within a burial depth of 4,500 m in Xiong'an New Area. The reservoir evaluation method, a relatively mature approach, has been extensively applied in calculating hydrothermal resources in sedimentary basins (Wang et al. 2019). The extraction and reinjection balance method, based on the thermal breakthrough equation (Liu et al. 2016) and considering reinjection conditions, was used to calculate four key indicators for Jixianian geothermal reservoirs in different zones of Xiong'an New

Area: geothermal resources, geothermal fluid reserves, recoverable reserves of geothermal fluids, and recoverable heat of geothermal fluids.

The evaluation focuses on the geothermal reservoirs of the Jixianian Wumishan and Gaoyuzhuang formations within a burial depth of 4,500 m. Zoning was based on the tectonic units in the area, with parameters summarized in Table 4. Evaluation zone areas were determined using Mapgis software. Formation thickness was calculated from the roof and floor burial depths determined from borehole logs, And the reservoir thickness ratio was derived from borehole data and regional reference values. Geothermal reservoir temperature and porosity values were also sourced from borehole logs. For zones without geothermal wells, reservoir temperature were inferred using the geothermal gradient. The GWD was obtained by analyzing data from geothermal monitoring wells. The specific heat of water was set at 4,186.8 J/kg·°C, as specified in DZ/T 0331—2020, while water density was derived from geothermal reservoir temperatures in respective zones. The specific heat and density of rocks were obtained from measured core sample data from boreholes within the area. The total compressibility coefficient of Jixianian geothermal reservoirs was determined to be 3.6 MPa^{-1}, and the temperature of the constant temperature layer was set at 14.5°C, respectively.

The calculated values for geothermal resources and other indicators in various comprehensive evaluation zones, within a burial depth of 4,500 m, are shown in Table 5. The optimal exploitation zones for deep geothermal resources (scores ≥6.8) cover an evaluation area of 195.25 km^2. In these zones, the Jixianian geothermal reservoirs demonstrate the following characteristics:

• Geothermal resources: 948.31×10^{16} J;
• Geothermal fluid reserves: 20.86×10^8 m^3;
• Recoverable geothermal fluids: 18.78×10^4 m^3/d under extraction and reinjection balance;
• Recoverable heat of geothermal fluids: 1.69×10^{16} J/a under extraction and reinjection balance.

These values are equivalent to 57.7×10^4 t/a of standard coal, supporting a heating area of 4,657× 10^4 m^2. Overall, the Jixianian geothermal carbonate reservoirs across Xiong'an New Area, excluding the area of Baiyangdian Lake, span a total evaluation area of 1,605.64 km^2. These reservoirs demonstrate the following:

• Geothermal resources: 5,370.31×10^{16} J;
• Geothermal fluid reserves: 101.17×10^8 m^3;
• Recoverable geothermal fluid reserves: 93.41×10^4 m^3/d under extraction and reinjection

Table 4 Summary of main calculation parameters in the study area

Layer	Score	Structure position	Zoning area (km²)	Thickness of Jixianian strata (m)	Thickness of geothermal reservoir (m)	GWD (m)	Porosity (%)	Geothermal reservoir temperature (°C)	Specific heat of water (kg/m³)	Water density (J/kg·°C)	Density of rocks (kg/m³)	Specific heat of rocks (J/kg·°C)	Elastic storativity (10^{-5})
Wumishan Formation	>6.8	Central uplifted area of the Rongcheng Uplift	64.77	800	240	120	4.0	70	980.00	4,186.8	2,600	879.23	3.32
		Axis of the Niutuozhen Uplift	70.16	1,000	250	115	3.5	70	971.82	4,186.8	2,600	879.23	3.00
		Axis of the Niutuozhen Uplift	45.48	800	200	115	3.5	80	971.82	4,186.8	2,600	879.23	2.40
		The Dianbei trough the southern Niutuozhen Uplift	14.84	1,000	200	110	3.0	80	971.83	4,186.8	2,600	879.23	2.06
	5.6	Central uplifted area of the Rongcheng Uplift	83.08	400	120	110	4.0	62	983.00	4,186.8	2,600	879.23	1.67
	-6.8	the western slope area of the Rongcheng Uplift	86.25	600	240	114	3.5	62	980.00	4,186.8	2,600	879.23	2.91
		The western slope area of the Niutuozhen Uplift	64.99	1,000	250	110	3.5	75	971.82	4,186.8	2,600	879.23	3.00
		The transition zone between the Niutuozhen Uplift and the Bazhou Sag	88.39	400	60	110	3.0	75	971.82	4,186.8	2,600	879.23	0.62
		The transition zone between the Niutuozhen Uplift and the Bazhou Sag	78.39	1,000	200	110	3.0	75	971.82	4,186.8	2,600	879.23	2.06
		The western area of the Gaoyang Low Uplift	180.72	600	120	125	3.0	110	942.80	4,186.8	2,600	879.23	1.20
		The eastern area of the Gaoyang Low Uplift	151.10	1,000	160	125	3.0	105	943.00	4,186.8	2,600	879.23	1.60
	4.4	The western slope area of the Rongcheng Uplift	55.41	400	120	114	3.5	72	980.00	4,186.8	2,600	879.23	1.45
	-5.6	The eastern trough area of the Rongcheng Uplift	39.12	800	240	112	3.5	85	968.00	4,186.8	2,600	879.23	2.87
		The eastern trough area of the Rongcheng Uplift	54.43	1,000	250	105	3.5	80	971.82	4,186.8	2,600	879.23	3.00
		The western slope area of the Niutuozhen Uplift	66.99	800	200	110	3.5	75	971.82	4,186.8	2,600	879.23	2.40
		The Bazhou Sag	99.66	200	40	110	3.0	85	971.82	4,186.8	2,600	879.23	0.41
		The eastern of the Gaoyang Low Uplift---the Lixian slope	64.32	1,000	160	120	3.0	105	943.00	4,186.8	2,600	879.23	1.60
		The eastern area of the Gaoyang Low Uplift	92.40	800	80	100	3.0	105	943.00	4,186.8	2,600	879.23	0.80
		The western area of the Gaoyang Low Uplift	85.20	300	60	125	3.0	110	942.80	4,186.8	2,600	879.23	0.60

Table 4 (continued)

Layer	Score	Structure position	Zoning area (km²)	Thickness of Jixianian strata (m)	Thickness of geothermal reservoir (m)	GWD (m)	Porosity (%)	Geothermal reservoir temperature (°C)	Specific heat of water (kg/m³)	Water density (J/kg·°C)	Density of rocks (kg/m³)	Specific heat of rocks (J/kg·°C)	Elastic storativity (10⁻⁵)
	4.1-4.4	The eastern area of the Rong-cheng Uplift	18.51	600	120	125	3.0	110	942.8	4,186.8	2,600	879.228	1.20
		The Bazhou Sag	68.01	150	30	110	3.0	85	971.82	4,186.8	2,600	879.23	0.31
	<3.5	The eastern trough area of the Rongcheng Uplift	33.41	100	30	112	3.5	70	974.00	4,186.8	2,600	879.23	0.36
Gaoyuzh-uang Formation	>6.8	Central uplifted area of the Rongcheng Uplift	64.77	1,000	150	120	2.0	70	978.00	4,186.8	2,600	879.23	1.04
		Axis of the Niutuozhen Uplift	45.48	500	75	115	2.0	85	965.32	4,186.8	2,600	879.23	0.51
		Axis of the Niutuozhen Uplift	70.16	1,000	150	115	2.0	90	965.32	4,186.8	2,600	879.23	1.02
	5.6	Central uplifted area of the Rongcheng Uplift	83.08	800	160	110	2.0	75	980.00	4,186.8	2,600	879.23	1.11
	-6.8	The western slope area of the Rongcheng Uplift	86.25	900	135	116	3.0	70	980.00	4,186.8	2,600	879.23	1.40
		The western slope area of the Niutuozhen Uplift	64.99	1,000	150	110	2.0	90	965.32	4,186.8	2,600	879.23	1.02
		The transition zone between the Niutuozhen Uplift and the Bazhou Sag	88.39	800	104	115	2.0	90	965.32	4,186.8	2,600	879.23	0.71
		The transition zone between the Niutuozhen Uplift and the Bazhou Sag	78.39	500	65	115	2.0	90	965.32	4,186.8	2,600	879.23	0.44
	4.4	The western area of the Rong-cheng Uplift	55.41	800	120	119	3.0	70	980.00	4,186.8	2,600	879.23	1.25
	-5.6	The western slope area of the Niutuozhen Uplift	34.04	600	90	112	2.0	90	965.32	4,186.8	2,600	879.23	0.61
		The eastern trough area of the Rongcheng Uplift	39.12	600	90	112	2.0	90	961.00	4,186.8	2,600	879.23	0.61
		The eastern trough area of the Rongcheng Uplift	54.43	800	120	110	2.0	80	965.32	4,186.8	2,600	879.23	0.82
		The Bazhou Sag	99.66	500	65	115	2.0	90	965.32	4,186.8	2,600	879.23	0.44
	4.1-4.4	The Bazhou Sag	68.01	500	65	115	2.0	90	965.32	4,186.8	2,600	879.23	0.44
	<3.5	The eastern trough area of the Rongcheng Uplift	33.41	150	23	110	2.0	75	968.00	4,186.8	2,600	879.23	0.15

Table 5 Results of resource calculations

Regionalization score	Zoning area (km^2)	Geothermal resources (10^{16}J)	Geothermal fluid reserves (10^8 m^3)	Recoverable reserves of geothermal fluids (10^4 m^3/d)	Recoverable heat of geothermal fluids (10^{16} J/a)
＞6.8	195.25	948.31	20.86	18.78	1.69
5.6-6.8	732.93	2,624.65	48.33	45.31	4.569
4.4-5.6	557.53	1,613.06	29.28	26.47	2.788
3.5-4.4	86.52	160.66	2.19	2.35	0.274
＜3.5	33.41	23.62	0.50	0.50	0.042
total	1,605.64	5,370.31	101.17	93.41	9.36

balance;

• Recoverable heat of geothermal fluids: 9.36× 10^{16} J/a under extraction and reinjection balance.

These are equivalent to 319.4×10^4 t/a of standard coal, facilitating a heating area of 25,794×10^4 m^2.

4 Conclusions

This stucy conducted zoning research and potential evaluation for the exploitation and utilization of deep geothermal resources in Xiong'an New Area, leading to the following conclusions and insights:

(1) Geothermal zoning research: Comprehensive research was performed on the spatial distribution of geothermal reservoirs in the Jixianian Wumishan and Gaoyuzhuang formations, which serve as the primary reservoirs for exploitation and utilization in the area. Based on factors related to the characteristics and conditions of Jixianian geothermal resources, six evaluation factors were selected as zoning indicators. By employing fuzzy mathematics, zoning research was carried out for the exploitation and utilization of geothermal resources in Jixianian geothermal reservoirs, yielding quantitative evaluation scores and identifying the distributions of favorable zones.

The quantitative evaluation revealed that favorable zones for exploiting deep geothermal resources (scores ≥6.8) in Xiong'an New Area are generally suitable for large-scale exploitation. These zones are primarily tectonically located in the Rongcheng and Niutuozhen uplift zones. For other areas, geothermal resource utilization and development should align with specific geothermal indicators. Additionally, zones with comprehensive scores of ≤3.5, influenced by the Rongcheng fault, exhibit extremely varying formation thicknesses. Exploration wells in these areas indicate low productivity, and exploitation is not recommended.

(2) Geothermal potential evaluation: Using the reservoir evaluation method, the Jixianian geothermal carbonate reservoirs within a burial depth of 4,500 m in Xiong'an New Area exhibit the following resource estimates:

• Geothermal resources: 5,370.31×10^{16} J;

• Geothermal fluid reserves: 101.17×10^8 m^3;

• Recoverable geothermal fluid reserves: 93.41 ×10^4 m^3/d under extraction and reinjection balance;

• Recoverable heat of geothermal fluids: 9.36 ×10^{16} J/a under extraction and reinjection balance.

These values are equivalent to 319.4×10^4 t/a of standard coal, supporting a heating area of 25,794×10^4 m^2.

Xiong'an New Area exhibits favorable conditions for geothermal resource occurrence, making it highly suitable for exploitation and utilization. Zones with favorable occurrence conditions should be prioritized for large-scale exploitation and utilization through intensified efforts. Zones with high resource potential but significantly varying occurrence conditions are recommended as as key exploration zones, requiring enhanced evaluations of deep Jixianian geothermal reservoirs to ensure resource security and reduce risks associated with exploitation and utilization. Zones near the Rongcheng fault or Jixianian strata at burial depths exceeding 4000 m are suggested for postponed exploitation. Overall, the exploration and exploitation of geothermal resources in Xiong'an New Area should be guided by local resource conditions and surrounding industrial planning needs.

Acknowledgments

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