



OPEN ACCESS

EDITED BY

Qingchao Li,
Henan Polytechnic University, China

REVIEWED BY

Haowei Yuan,
China University of Petroleum, Beijing, China
Liang He,
Nanjing Xiaozhuang University, China

*CORRESPONDENCE

Rui Lu,
✉ 1125207830@qq.com
Bo Liu,
✉ 50013842@qq.com

RECEIVED 27 October 2025

REVISED 17 December 2025

ACCEPTED 29 December 2025

PUBLISHED 09 February 2026

CITATION

Xie W, Lu R, Liu B, Zhu J, Cai J, Zhang D and Wang X (2026) Comprehensive evaluation and zoning study of potential geothermal water resources in Qinghai Province, northeastern margin of the Tibetan Plateau. *Front. Earth Sci.* 13:1733233. doi: 10.3389/feart.2025.1733233

COPYRIGHT

© 2026 Xie, Lu, Liu, Zhu, Cai, Zhang and Wang. This is an open-access article distributed under the terms of the [Creative Commons Attribution License \(CC BY\)](#). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Comprehensive evaluation and zoning study of potential geothermal water resources in Qinghai Province, northeastern margin of the Tibetan Plateau

Wenping Xie^{1,2}, Rui Lu^{1,2*}, Bo Liu^{1,2*}, Jinshou Zhu^{1,2}, Jinshou Cai³, Deseng Zhang⁴ and Xianrong Wang^{1,2}

¹Qinghai Geological Survey Bureau, Xining, China, ²Technology Innovation Center for Exploration and Exploitation of Strategic Mineral Resources in Plateau Desert Region, Ministry of Natural Resources, Xining, China, ³Institute of the Hydrogeology and Engineering Geology of Qinghai, Xining, China, ⁴Tianjin Geothermal Exploration and Development Design Institute, Tianjin, China

The geothermal resources in Qinghai Province are endowed with superior potential, yet overall exploration remains at a relatively low and spatially uneven level. Most sedimentary basins and structural fault zones within the province have not undergone systematic exploration, leading to relatively high exploration risks. To address this challenge, this study developed a novel semi-quantitative methodology that integrates basin heat storage and tectonic heat control theories, breaking through the traditional “heat-following” exploration paradigm. The study divides the province’s hydrothermal resources into 16 potential sedimentary basin (conductive-type) zones and 32 potential fault zones (mountain uplift convective-type). Based on genetic elements of “source-pathway-cap-reservoir-flow,” a multidimensional evaluation index system was established. Innovatively combining the analytic hierarchy process (AHP) and principal component analysis (PCA), this research quantitatively assessed the resource potential of each zone and classified the potential levels using the quartile method. By integrating the evaluation results from both approaches, a total of 32 geothermal resource prospective areas were delineated across the province, including 10 sedimentary basin-type and 22 fault zone-type areas. Building on this, and closely considering resource potential, population distribution, regional development plans, and preliminary environmental screening, 10 target areas were prioritized for early-stage exploration deployment. The research outcomes provide a systematic scientific basis for strategic planning and governmental decision-making regarding the exploration and development of geothermal resources in Qinghai Province.

KEYWORDS

evaluation indicators, geothermal resources, northeastern margin of the Tibetan Plateau, potential zoning, target area optimization

1 Introduction

Geothermal energy, as a clean, stable, and sustainable renewable energy source, is strategically important to the global low-carbon energy transition. China is rich in

geothermal resources with broad prospects for development and utilization. Systematically advancing the exploitation and use of geothermal resources is of great significance for alleviating energy supply–demand contradictions, driving high-quality regional economic development, and strengthening the national energy security barrier (Lin et al., 2013; Hu et al., 2013; Pang et al., 2020; Qiu et al., 2022; Wang and Gong, 2017). Located on the northeastern margin of the Tibetan Plateau at the forefront of the India–Eurasia plate collision zone, Qinghai Province experiences intense neotectonic activity and possesses favorable deep heat flow conditions (Li J. et al., 2025; Chen et al., 2025; Zhang et al., 2025). This has led to the formation of diverse types and abundant reserves of geothermal resources, making it one of the core regions for both national ecological security and clean energy bases.

Guided by the “dual carbon” goals and leveraging its superior geological conditions and policy support, Qinghai Province has implemented over 80 geothermal survey and research projects. Significant progress has been made in areas such as the exploration of hydrothermal resources and hot dry rock in the Gonghe–Guide Basin and the utilization of high-salinity geothermal resources in the Xining Basin (Tang et al., 2020; 2023; Yun et al., 2020; Zhang C. et al., 2020; Zhang S. et al., 2020; Zhang S. et al., 2021; Zhang Y. et al., 2021; Lin et al., 2023;

Zhang et al., 2024; Liu et al., 2024). Regarding resource potential assessment, Wang et al. (2017) have conducted classified evaluations of different types of geothermal resources in China. Qinghai Province has also carried out assessments of the current resource status, focusing on key basins (Yang et al., 2015; Zhang et al., 2015; Lu et al., 2024). However, traditional assessment standards and case studies have predominantly focused on calculating heat reservoir resources and fluid quality (Natural Resources and Territory Spatial Planning, 2011; 2020; Technical Committee on Standardization of Geothermal Energy of the Energy Industry, 2020; 2021; Qiu et al., 2019; Wang et al., 2024; Zhu et al., 2024), failing to systematically integrate the genetic elements of the geothermal system “source, pathway, caprock, reservoir, and fluid” for a comprehensive evaluation of potential.

Addressing the needs of Qinghai Province’s geothermal resource development planning and the shortcomings of existing evaluation methods, this study aims to break through traditional approaches by constructing a semi-quantitative comprehensive evaluation system applicable to both conductive resources in sedimentary basins and convective resources in uplifted mountainous areas. The innovation of this research is reflected in three aspects: 1. proposing a conceptual model for optimizing exploration targets that integrates the theories of “basin heat storage” and “tectonic

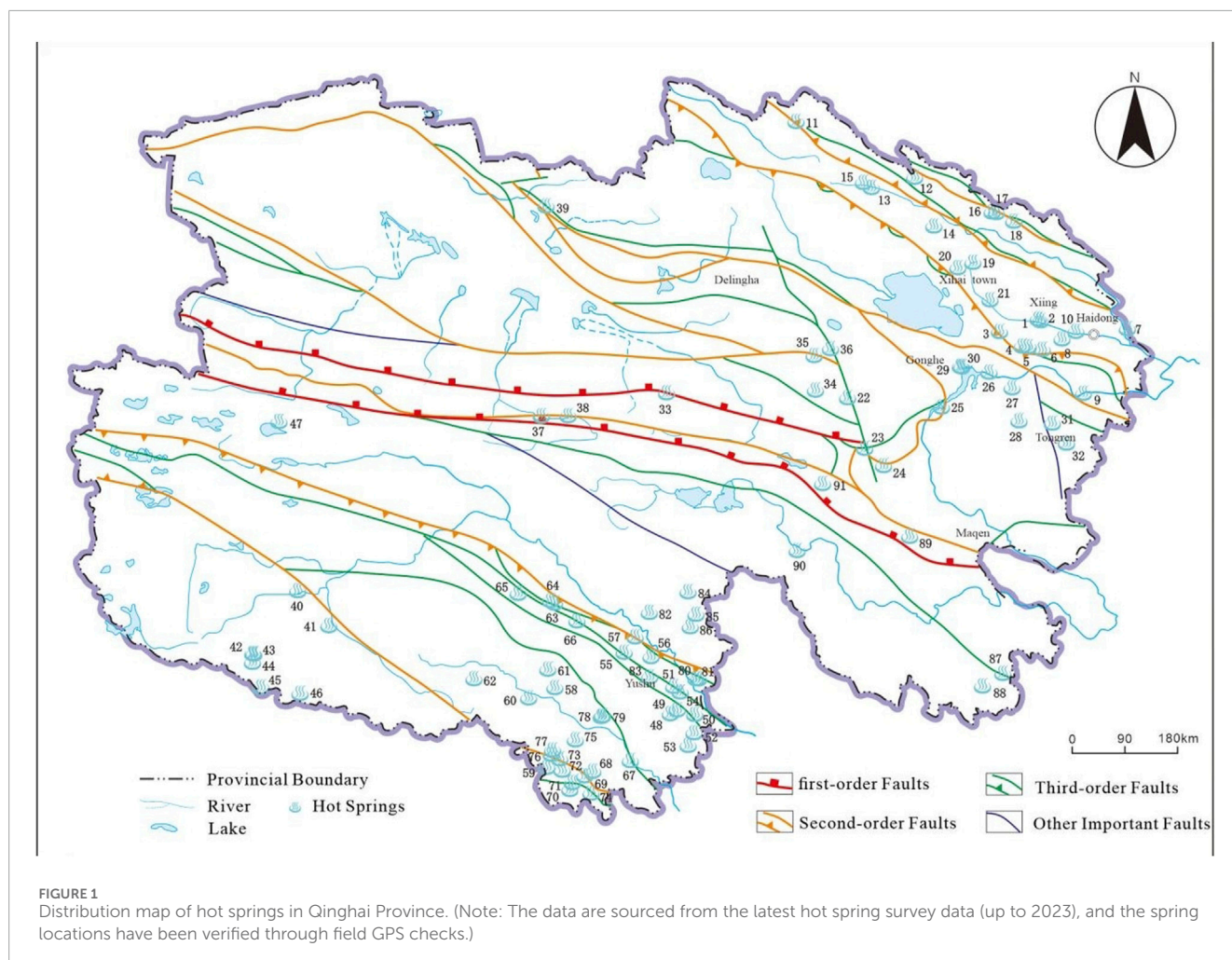


FIGURE 1 Distribution map of hot springs in Qinghai Province. (Note: The data are sourced from the latest hot spring survey data (up to 2023), and the spring locations have been verified through field GPS checks.)

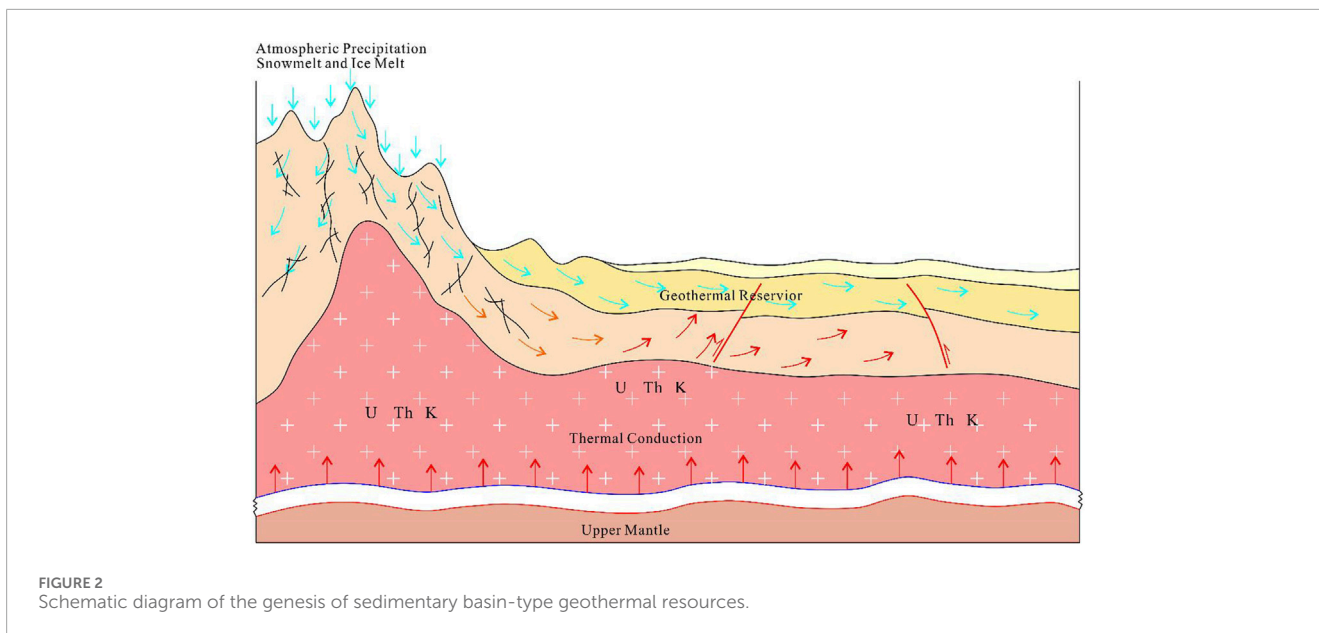
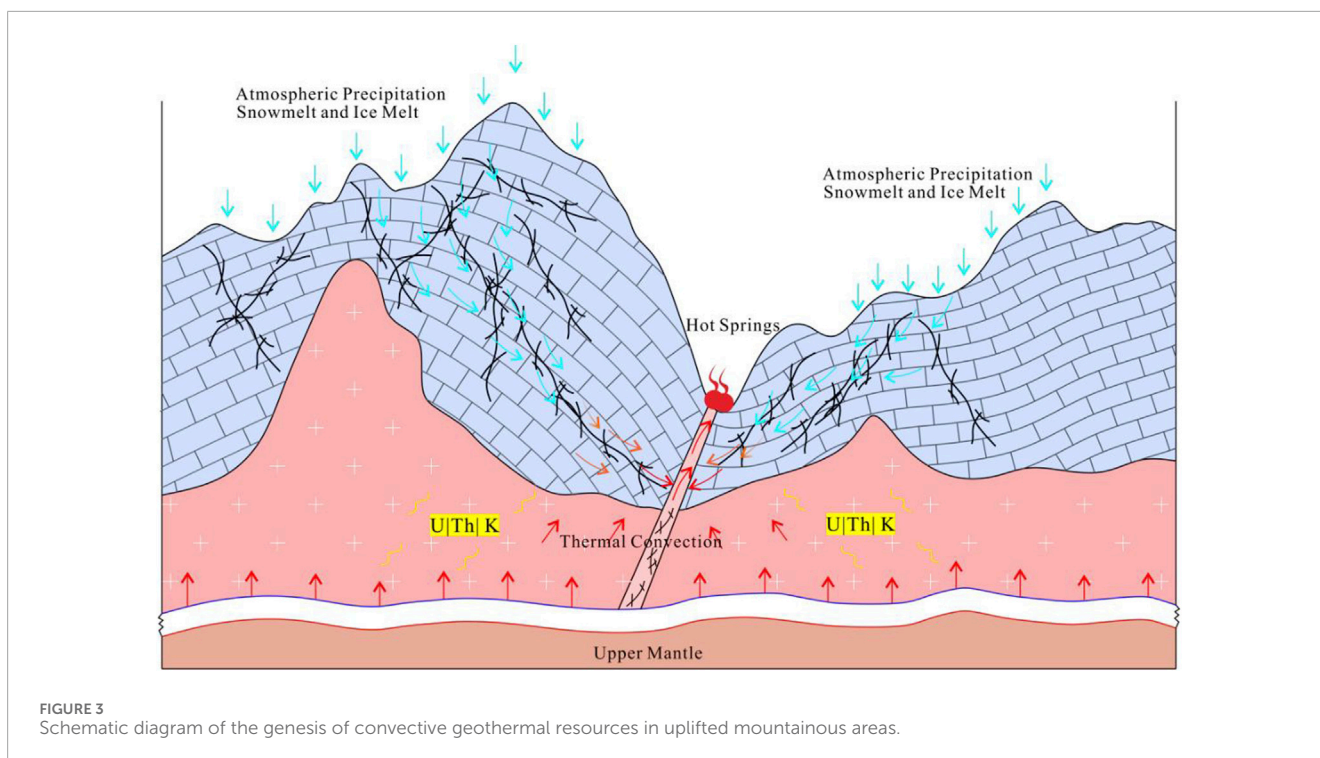


TABLE 1 Overview of major sedimentary basin-type geothermal resources.

No.	Basin name	Sedimentary era	Formation mechanism	Representative wells/Springs
1	Qaidam Basin	E-N	Fault-depression	5 oilfield wells in W/NW part, 25.0 °C–65.0 °C
2	Hala Lake Basin	E3-N	Fault	No geothermal anomaly
3	Suli Basin	N	Fault	No geothermal anomaly
4	Minhe Basin	E-N	Fault-depression	1 geothermal well, 64 °C; 1 spring, 24 °C
5	Xining Basin	E-N	Fault-depression	19 geothermal wells, 27 °C–62.5 °C; 6 springs, 9 °C–41 °C
6	Xunhua and Hualong basins	E-N	Fault	1 spring, 26 °C
7	Gonghe Basin	N	Depression	22 geothermal wells, 73 °C–105 °C; 6 springs, 20.0 °C–35.0 °C
8	Xinghai–Zeku Basin	N	Fault	3 springs, 13 °C–78 °C
9	Dongdatan Basin	N	Pull-apart	2 geothermal wells, 25.6 °C–60 °C; 3 springs, 11 °C–57 °C
10	Hoh Xil–Tuotuohe Basin	E-N	Fault-depression	1 spring, > 90 °C
11	Mado Residual Basin	E-N	Pull-apart	1 spring, 21 °C–27.5 °C
12	Qumarleb Basin	E-N	Pull-apart	No geothermal anomaly
13	Nangqen Basin	E-N	Pull-apart	13 springs, 18 °C–62 °C
14	Tongren Basin	E-N	Fault	1 geothermal well, bottom temp. 90 °C; 2 springs, 48 °C–82 °C
15	Menyuan Basin	N	Fault	3 springs, 13 °C–20 °C
16	Tanggula Hot Spring Basin	T	Fault	7 springs, 19 °C–68 °C

heat control;” 2. establishing a multi-factor, semi-quantitative evaluation index system based on the genetic elements of the geothermal system; 3. adopting a combined subjective-objective (analytic hierarchy process (AHP) and principal component

analysis (PCA)) analytical method to increase the reliability of potential zoning results. The research findings aim to provide a direct scientific basis for the exploration and planning of geothermal resources in Qinghai Province, as well as to offer



a new methodological reference for resource assessment in similar regions.

2 Overview of geothermal resources in the study area

2.1 Distribution of geothermal resources

Qinghai Province, located on the northeastern margin of the Tibetan Plateau, possesses a rich and diverse geothermal resource pattern shaped by its unique geotectonic background and superior geothermal geological conditions. All three types of geothermal resources—shallow geothermal energy, underground hot water, and hot dry rock—have been identified. Among them, hydrothermal resources are widely distributed across all eight prefectures/cities of the province, and are characterized by shallow burial and high temperatures. A total of 91 natural thermal spring outcrops have been discovered in the province (Figure 1), including 20 hot water points (60 °C~90 °C), 14 warm water points (40 °C~60 °C), 24 tepid water points (25 °C~40 °C), and 33 low-temperature water points (below 25 °C). Additionally, there are 84 geothermal anomaly wells, including seven medium-temperature geothermal wells (≥ 90 °C, mainly distributed in Hainan Prefecture), 25 low-temperature hot water wells (60 °C~90 °C), 21 low-temperature warm water wells (40 °C~60 °C), 21 low-temperature tepid water wells (25 °C~40 °C), and 10 wells with significant geothermal gradient anomalies that are not pumped. According to the latest resource assessment, the total mid-deep geothermal energy resource in the province amounts to 475.754 billion tons of standard coal. Calculating with a 10% recovery rate for geothermal energy from the thermal reservoir, the total recoverable resource is 47.5754 billion tons of standard

coal, of which the controlled recoverable resource is 172 million tons, and the inferred recoverable resource is 47.404 billion tons of standard coal (Lu et al., 2024).

2.2 Types of geothermal resources

Based on the hydrodynamic characteristics, storage conditions, geological structure, and heat conduction systems of underground hot water in Qinghai Province, combined with regional geothermal genetic theory, and starting from the key elements controlling geothermal resource enrichment and occurrence, the hydrothermal resources are classified into two basic types according to the geological elements of “source–pathway–cap–reservoir–fluid” and the characteristics of heat transfer, storage, preservation, and dissipation: sedimentary basin conductive type and uplifted mountainous area convective type.

2.2.1 Sedimentary basin conductive type geothermal resources

Controlled by recent tectonic activity, the strong uplift of the Qilian, Kunlun, and Tanggula mountains led to the relative subsidence of the plains between them, forming a series of basins of varying sizes, such as Qaidam, Haiyan, Gonghe, Xining, Guide, and Tongren. These basins are filled with thick clastic sedimentary sequences, providing favorable space for the formation and occurrence of underground hot water (Zhang et al., 1992; Song et al., 2003; Du et al., 2011; Li et al., 2013). The basins are often bounded by deep faults, which are large-scale, long-extending, and often form a series of secondary fault zones, serving as good channels for fluid migration. Atmospheric precipitation and snowmelt infiltrate through the mountainous areas surrounding

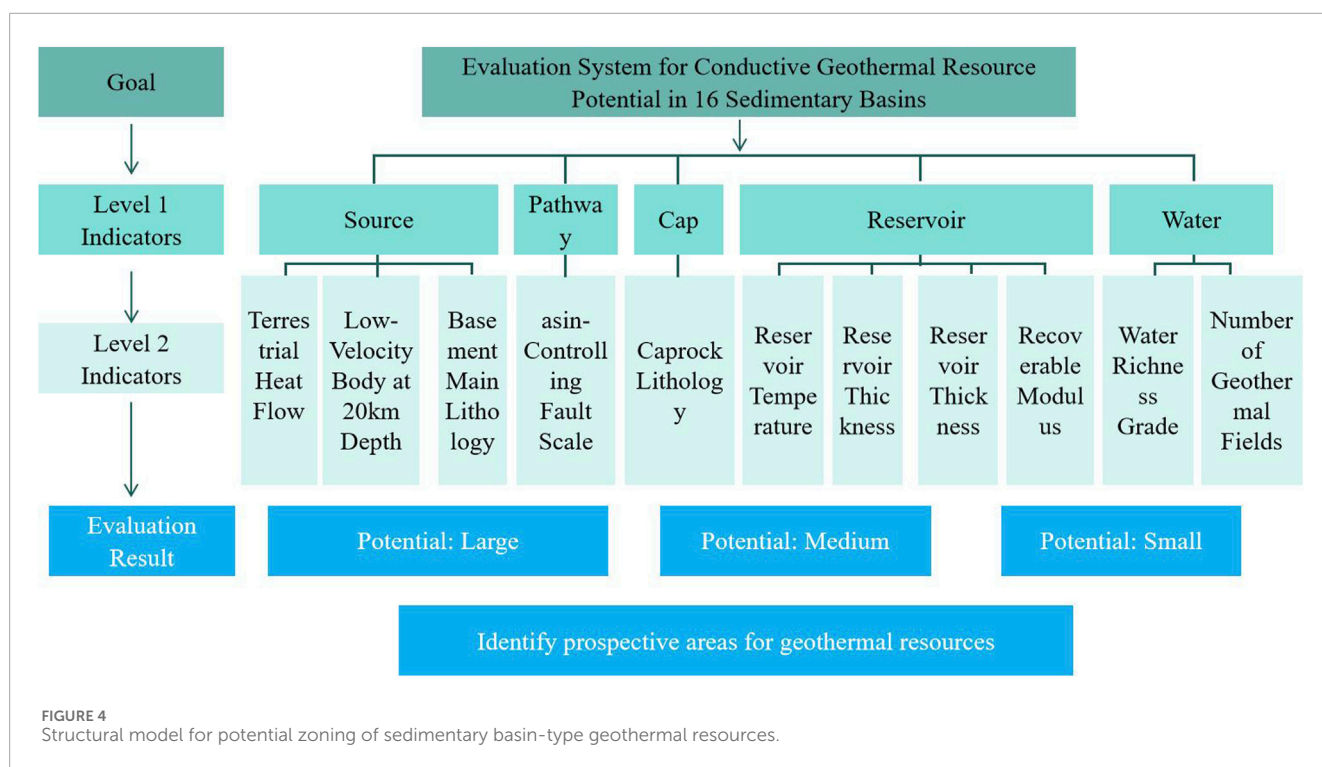
TABLE 2 Overview of major uplifted mountainous area-type geothermal resources.

Fault name	Distribution of geothermal anomalies along the fault
Altyn Tagh fault F1	No geothermal anomalies have been discovered along this fault yet
Lenglongling north margin fault F2	Springs along fault: Qilian Binggoucun North, Menyuan Shizikou, Liuhuanguo, Gangshika Snow Mountain, 13 °C–20 °C. A well at Qilian DR1 revealed a temperature of 36 °C
Baoku River–Ebao fault F3	Springs along fault: Qilian Binggoucun North, Menyuan Shizikou, Liuhuanguo, Gangshika Snow Mountain, 13 °C–20 °C. A well at Qilian DR1 revealed a temperature of 36 °C
Dabanshan north margin fault F4	Springs along fault: Qilian Tuolehe Jiabo, and Gangcha Datong River upstream, hot water coal mine, Jiangcang coal mine, Haiyan Baohutu River upstream, 32 °C–57 °C
Shulenshan–Lajishan north margin fault F6	Springs: Gangcha hot water coal mine, Haiyan Ganzi River, Huangyuan Yaoshuicun, Huangzhong Yaoshuitan, Mendanxia, Ping'an Binglingshan, generally low, 18 °C–46 °C
Lajishan south margin fault F7	Geothermal wells in Huangyuan Xuelong village and Huangzhong Yaoshuitan have temperatures of 31 °C–41 °C
Zongwulongshan–Qinghainan Shan fault F8	Springs: Gonghe Xiernalongwakecai, Ayihai, >25 °C. Wells in Xunhua County Town–Cailan Base, Xunhua Bolangtan reveal temperatures. 26 °C–45 °C, yield 275–485.4 m ³ /d, clear anomaly
Olongbuluke north margin fault F10	Nearby: Da Qaidam Spring Group, 63 °C–70 °C. A well at Da Qaidam, within 160 m depth, has temperatures of 58.5 °C–72.3 °C.
Saishiteng–Wanggaixiu fault F11	No geothermal anomalies have been discovered yet.
Qaidam Basin north margin fault F12	Dayantan oil wells and Niulang Zhinv well temperatures: 25 °C–37 °C. A well at Chai 10: at 4,200 m depth, the temperature is 132 °C
Lianhuashi–Xiaolangyashan fault F14	No anomalies discovered near this fault to date
Adatan–Wulanwuzhu'er south margin fault F15	Near intersection with Kunbei fault: Dulan County Angutan and Chahanwusu Springs, 67 °C–87 °C
Kunnan fault F18	Springs along fault: Golmud Wenquan reservoir upstream group, Maqin Dongqinggou, 27 °C–90 °C
Buqingshan south margin fault F19	Springs along fault: Golmud Xiugou East, Mado Huashixia Zhuo'erla, 27.5 °C–39 °C
Wahongshan–Wenquan fault F20	Springs: Wulan Bahynggeligou, Xinghai Sangchigou, 44 °C–62 °C
Wenquan–Qijia fault F21	Near intersection with Kunbei fault: Xinghai Wenquan Township Spring, 64 °C. Well Xinghai Wenquan Township, outlet temp. 61 °C–63 °C
Guide–Duohemao fault F23	Springs along fault: Guide Qunaihai, Zhacang Temple, Xinjie Township, Tongren Lancai, Qukuhu, generally high, Zhacang Temple, up to 98 °C
Zequ–Tuoyema fault F24	No anomalies have been discovered near this fault to date
Kunlunkou–Gande fault F25	Spring along fault: Bamma Keke River, high temp. 90 °C, large flow 10.085 L/s
Dangjiang–Zhimenda fault F28	Springs along fault zone: Zhiduo White Conch, Zhiduo Gongsai Temple, Yushu Anchongxiang Dairang Village Angpu Temple, Yushu Anchong Chalong, Chenduo Dangbagou mouth, Chenduo Dangba, 23.5 °C–65 °C
Xijir Ulan north–Yushu fault F29	Springs along fault zone: Yushu Batang River, Yushu Shabajiu Princess, Yushu Longbao Equunqu, Zhiduo Riqing Dangjiang, Chenduo Zhaduo Shai Chai, 12.5 °C–38 °C
Bamqu–Gela fault F30	Springs along fault zone: Yushu hot water gully upstream, Leyongda, Yushu hot water gully Hasang Chaguo, Yushu Xiaosumang Xiqu Tuoji, Yushu Xiaosumang Benjiang Village, 35 °C–65 °C
Wuli–Nangqen fault F31	Springs along fault: Nangqen Juola, Nangqen Xiangda North mountain, Nangqen Juola Xiangba, Zaduo Zhagou upstream, 18 °C–38 °C
Wulanwula north margin–Jieduo fault F32	No anomalies discovered near this fault to date.
Wulanwula south margin fault F33	Springs along fault: Qinghai–Tibet Highway Gaizhai, Yanjiping East, Zaduo Zhagou, Nangqen Jinixai Zongga, Gaxiang Chatan Village Jiaweng, 19 °C–59 °C

(Continued on the following page)

TABLE 2 (Continued) Overview of major uplifted mountainous area-type geothermal resources.

Fault name	Distribution of geothermal anomalies along the fault
Tanggula south margin fault F35	Springs along fault: Nangqen Jinixai Dana, Nangqen Jinixai Dana Maiqu, Nangqen Jinqi Waka Village Wankang, 19 °C–62 °C
Zhongtie fault	Near starting point: Xinghai Wenquan Township Spring, 64 °C. A well at Xinghai Wenquan Township, outlet temp. 61 °C–63 °C
Qaidam Basin north-central fault	Along the fault: Nanbaxian oil wells, Niulang Zhinv well temps. 25 °C–37 °C. A well at Taiji Shen 1#: at 3,900 m depth, the temperature is 120 °C
Qaidam Basin south-central fault	Along fault: Wells Taiji 7, Cha 8, Se 40, Tuo 2, Yanxi 2, at 800 m depth, the temperature is 40 °C; at 2,000 m depth, the temperature ranges up to 70 °C.
Wudaoliang–Qumarleb fault	Springs along fault zone: Zhiduo White Conch, Zhiduo Gongsai Temple, Yushu Anchongxiang Dairang Village Angpu Temple, Yushu Anchong Chalong, Chenduo Dangbagou mouth, Chenduo Dangba, 23.5 °C–65 °C
Tanggula Hot Spring Basin fault	Springs along fault: Tanggulashan Town Station, Tanggulashan Town Station SE 800 m, Tanggulashan Town Station S ~8 km Riail, 63 °C–68 °C
Mangya Youshashan fault	Spring along fault: Dulan Angutan, 67 °C



the basins and are heated conductively by the surrounding rocks during groundwater flow toward the basin interior. The water accumulates in layered thermal reservoirs within coarse clastic layers with high porosity and permeability, overlain by low thermal conductivity caprocks providing insulation, ultimately forming sedimentary basin conductive-type underground hot water resources (Figure 2). Based on the basins delineated in the “Qinghai Regional Geology Annals,” this type of resource in the province mainly occurs in 16 basins, including Qaidam, Gonghe, Xining, and Tongren. Among these, 13 basins have already discovered thermal springs or have geothermal wells implemented (Table 1). These basins generally feature clear sedimentary boundaries, substantial

sedimentary thickness, anomalous geothermal gradients, and relatively high terrestrial heat flow values. Relatively high-temperature underground hot water has been explored in basins like Gonghe, Guide, and Xining.

2.2.2 Uplifted mountainous area convective-type geothermal resources

Also known as tectonic fissure type, these resources often manifest as springs on the surface, typically distributed linearly along tectonic fault zones, and are commonly found in zonal reservoirs formed by marginal fault zones of fault basins. Deep faults cutting through the crust or even extending into the

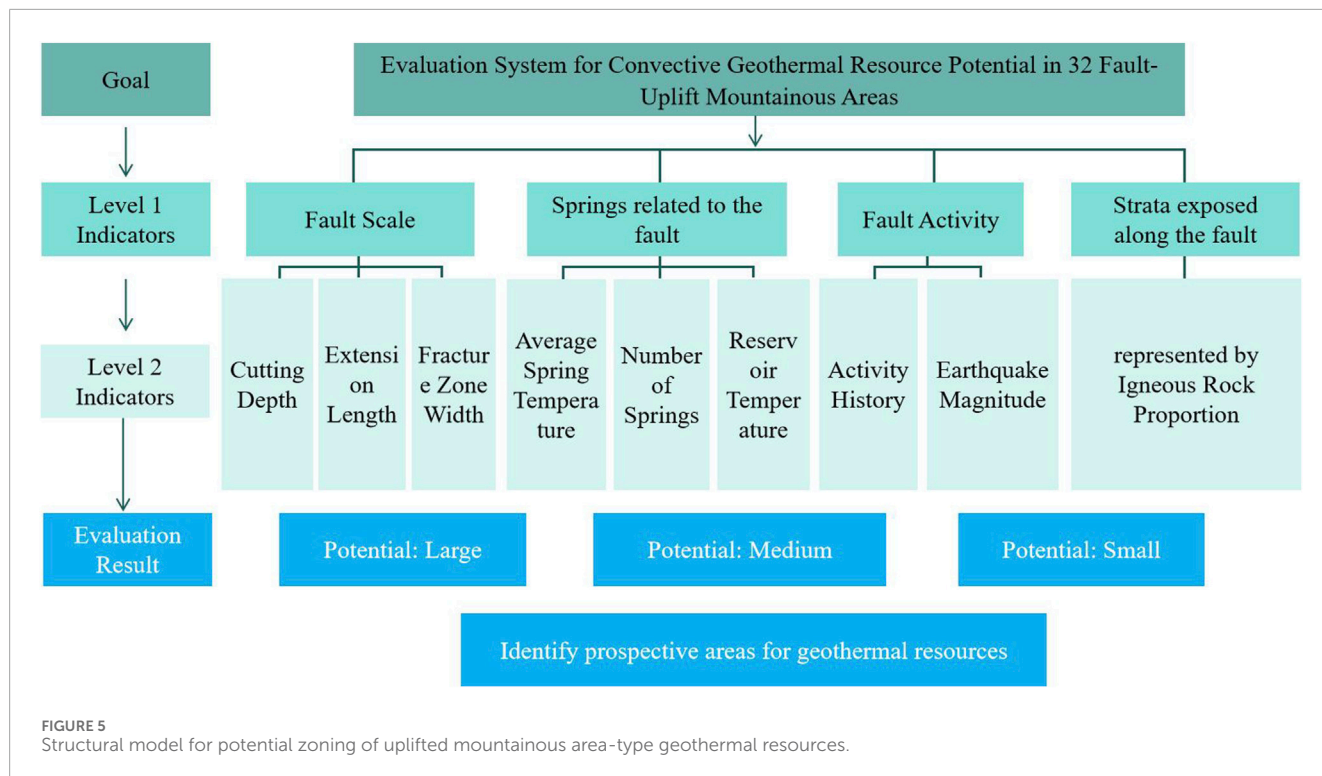


TABLE 3 List of indicator weights for the evaluation of potential sedimentary basin-type geothermal resources.

No.	Indicator	Weight (%)
1	Terrestrial heat flow value	22.22
2	Presence of a low-velocity body at 20 km depth	11.11
3	Main basement lithology	5.56
4	Basin-controlling fault scale	15.64
5	Caprock lithology	11.49
6	Reservoir temperature	7.67
7	Reservoir thickness	2.46
8	Reservoir lithology	1.57
9	Recoverable modulus	11.54
10	Water richness grade	5.37
11	Number of geothermal fields	5.37

mantle often form fault fracture zones of considerable scale or a series of secondary derivative faults. Geothermal manifestations occur at locations like fault fracture zones or intersections of faults with different orientations (Zhou et al., 2020; Zhou, 2007; Li X. et al., 2025). Atmospheric precipitation and snowmelt infiltrate and recharge in mountainous areas. Under conditions of generally low rock permeability, deep circulation and heat absorption occur primarily along fractures and fracture zones. Driven by

TABLE 4 List of indicator weights for the evaluation of potential uplifted mountainous area-type geothermal resources.

No.	Indicator	Weight (%)
1	Cutting depth	3.799
2	Extension length	0.914
3	Fracture zone width	1.082
4	Average spring temperature	13.541
5	Number of springs	3.459
6	Reservoir temperature	21.282
7	Activity history	8.553
8	Earthquake magnitude	25.659
9	Igneous rock proportion	21.711

topographic relief and hydraulic gradients, heated fluids ascend along highly permeable fracture zones and discharge as springs at favorable locations (e.g., intersections of fault sets), forming typical uplifted mountainous area convective-type underground hot water resources (Figure 3). This study first considered 2 first-order faults, 9 second-order faults, and 20 third-order faults from the “Qinghai Regional Geology Annals,” as well as 24 faults from the distribution characteristics of active faults in Qinghai Province as potential occurrence zones. After removing duplicates and faults without geothermal anomalies, combined with field surveys, 32

TABLE 5 Variance explanation table for evaluating the potential of sedimentary basin-type geothermal resource.

Component	Eigenvalue	% of variance	Cumulative %
1	2.692	29.909	29.909
2	1.754	19.484	49.393
3	1.481	16.455	65.848
4	0.966	10.728	76.577
5	0.715	7.94	84.517
6	0.662	7.352	91.869
7	0.407	4.523	96.392
8	0.314	3.486	99.878
9	0.011	0.122	100

TABLE 6 Variance explanation table for evaluating the potential of uplifted mountainous area-type geothermal resources.

Component	Eigenvalue	% of variance	Cumulative %
1	5.48	49.821	49.821
2	1.561	14.195	64.016
3	1.112	10.106	74.122
4	1.085	9.862	83.983
5	0.628	5.708	89.691
6	0.514	4.669	94.36
7	0.371	3.375	97.735
8	0.203	1.845	99.581
9	0.031	0.28	99.861
10	0.012	0.107	99.968
11	0.004	0.032	100

fault zones in the province were identified as hosting this type of resource (Table 2).

3 Research methods and process

To overcome the limitations of single subjective or objective evaluation methods, this study employs a comprehensive evaluation strategy that combines the analytic hierarchy process (AHP) and principal component analysis (PCA). AHP effectively integrates experts' empirical judgments on the genetic factors

of complex geothermal systems (Saaty, 1990; 2008; Vaidya and Kumar, 2006), while PCA extracts objective statistical patterns from multivariate data. The combination of both methods enhances the scientific rationality of the evaluation results (Abdi and Williams, 2010; Zou et al., 2006). Key indicators closely related to the occurrence of geothermal resources are selected to evaluate the geothermal resource potential of the study area. By comparing and overlaying the results of the two methods, the potential of different types of geothermal resources in the province is categorized into zones, including high-potential, medium-potential, and low-potential zones. All computational processes are implemented using SPSS software.

3.1 Construction of the potential area evaluation structural model

The 16 sedimentary basin geothermal resource occurrence areas in Qinghai Province are the evaluation objects for sedimentary basin conductive-type resources. Based on their geothermal geological characteristics, five first-level indicators (Source, Pathway, Cap, Reservoir, and Water) are selected and further subdivided into 11 second-level indicators: "Source" includes Terrestrial Heat Flow, Presence of Low-Velocity Body at 20 km depth, Basement Lithology; "Pathway" is Basin-controlling Fault Scale; "Cap" is Caprock Lithology; "Reservoir" includes Reservoir Thickness, Temperature, Lithology, and Recoverable Modulus; "Water" includes Water Richness Grade and Number of Geothermal Fields. A hierarchical model is built using these 11 indicators to evaluate the potential of different basins (Figure 4).

The 32 fault zones hosting this resource type are the evaluation objects for uplifted mountainous area convective-type resources. Four first-level indicators are selected: "Fault Scale, Springs related to the fault, Fault Activity, and Strata exposed along the fault," subdivided into nine second-level indicators: "Fault Scale" includes Cutting Depth, Extension Length, Fracture Zone Width; "Springs related to the fault" includes Average Spring Temperature, Number of Springs, Reservoir Temperature; "Fault Activity" includes Activity History, Earthquake Magnitude; "Strata exposed along the fault" is represented by Igneous Rock Proportion. A hierarchical model is built using these nine indicators to evaluate the potential of different fault zones (Figure 5).

3.2 Analytic hierarchy process (AHP)

AHP is a systematic, hierarchical decision-analysis method that decomposes a problem into different constituent factors and constructs a multi-level structural model according to their relationships, ultimately determining the relative weight or ranking of the underlying factors relative to the top-level goal (He et al., 2023; Zhang, 2022). The specific steps are as follows:

1. Construction of judgment matrices: Ten experts in the fields of geothermal geology, hydrogeology, and structural geology within the province were invited to provide scores using the 1–9 scale method, forming an $n \times n$ positive reciprocal judgment matrix A. The consistency ratio (CR) for each matrix

TABLE 7 Basic parameter assignment table for the evaluation indicators of potential sedimentary basin-type geothermal resources.

Basin name	Heat flow (mW/m ²)	Low-velocity body at 20 km?	Main basement lithology (thermal conductivity)	Basin-controlling fault scale	Caprock lithology	Reservoir temperature (°C)	Reservoir thickness (m)	Reservoir lithology	Recoverable modulus	Water richness grade	No. of geothermal fields
Gonghe	100	Yes	Intrusive rock + sandstone	Zongwulongshan-Qinghai Shan F8—lithospheric	Mudstone	67	378	Sandstone	52.59	Rich	8
Xining	65	No	Metamorphic rock	Shulianshan-Lajishan north margin F6—lithospheric	Mudstone	51	294	Sandstone	29.29	Medium	9
Qaidam	60	Yes	Sandstone	Kunlunkou-Gande F25—crustal	Sandy mudstone	55	630	Sandstone	73.35	Rich	1
Minhe	50	No	Metamorphic rock	Shulianshan-Lajishan north margin F6—lithospheric	Mudstone	55	630	Sandstone	65.44	General	0
Haiyan Dongdatan	45	No	Metamorphic rock	Dabanshan north margin F4—lithospheric	Sandy mudstone	40.5	252	Weathered crust + sandstone	22.32	General	1
Xinhua and Hualong	66.5	No	Metamorphic rock	Lajishan south margin F7—lithospheric	Metamorphic rock	27.5	105	Metamorphic rock	3.88	Poor	1
Xinghai-Zeku	46.8	No	Metamorphic rock	Wenquan-Qijia F21—basement	Sandy mudstone	37.5	210	Weathered crust + sandstone	17.00	General	1
Mado Residual	45	No	Metamorphic rock	Kunlunkou-Gande F25—crustal	Sandy mudstone	33	147	Metamorphic rock	11.92	Poor	0
Qumaleb-Zhiduo	54	No	Metamorphic + sandstone	Xijir Ulan North-Yushu F29—lithospheric	Mudstone	44.5	273	Sandstone + limestone	27.80	Medium	0
Nanggen	68	No	Limestone + intrusive	Wuli-Nanggen F31—basement	Mudstone	50	420	Sandstone + limestone	42.57	Medium	0

(Continued on the following page)

TABLE 7 (Continued) Basic parameter assignment table for the evaluation indicators of potential sedimentary basin-type geothermal resources.

Basin name	Heat flow (mW/m ²)	Low-velocity body at 20 km?	Main basement lithology (thermal conductivity)	Basin-controlling fault scale	Caprock lithology	Reservoir temperature (°C)	Reservoir thickness (m)	Reservoir lithology	Recoverable modulus	Water richness grade	No. of geothermal fields
Hala Lake	65	No	Sandstone	Shulenanshan-Lajishan north margin F6—lithospheric	Sandy mudstone	32	168	Metamorphic rock	11.59	Poor	0
Suli	65	No	Sandstone	Shulenanshan-Lajishan north margin F6—lithospheric	Sandy mudstone	32	168	Metamorphic rock	11.59	Poor	0
Hoh Xil-Tuotuohe	70	Yes	Intrusive + metamorphic	Xijir Ulan North-Yushu F29—lithospheric	Mudstone	47.5	315	Sandstone	36.46	Medium	0
Tongren	81	No	Sandstone + intrusive	Zongwulongshan-Qinghainan Shan F8—lithospheric	Mudstone	60	420	Sandstone	44.86	Poor	1
Menyuan	56	No	Limestone + sandstone	Lenglongjing north margin F2—lithospheric	Sandy slate	43	252	Sandstone + limestone	23.36	General	0
Tanggula Hot Spring	66	Yes	Limestone + intrusive	Tanggula south margin F35—lithospheric	Mudstone	52.5	315	Weathered crust + sandstone	40.06	General	0

TABLE 8 AHP potential evaluation results table.

No.	Basin name	AHP comprehensive score	Potential
1	Gonghe Basin	93.31	Large
2	Qaidam Basin	73.85	
3	Hoh Xil-Tuotuohe Basin	70.91	
4	Xining Basin	69.1	
5	Tongren Basin	69	Medium
6	Nangqen Basin	66.19	
7	Tanggula Hot Spring Basin	62.28	
8	Minhe Basin	60.38	
9	Qumarleb-Zhiduo Basin	53.49	
10	Menyuan Basin	45.56	
11	Haiyan Dongdatan Basin	44.55	
12	Hala Lake Basin	41.71	
13	Suli Basin	41.71	Small
14	Xinghai-Zeku Basin	41.21	
15	Xunhua and Hualong Basin	36.37	
16	Mado Residual Basin	35.31	

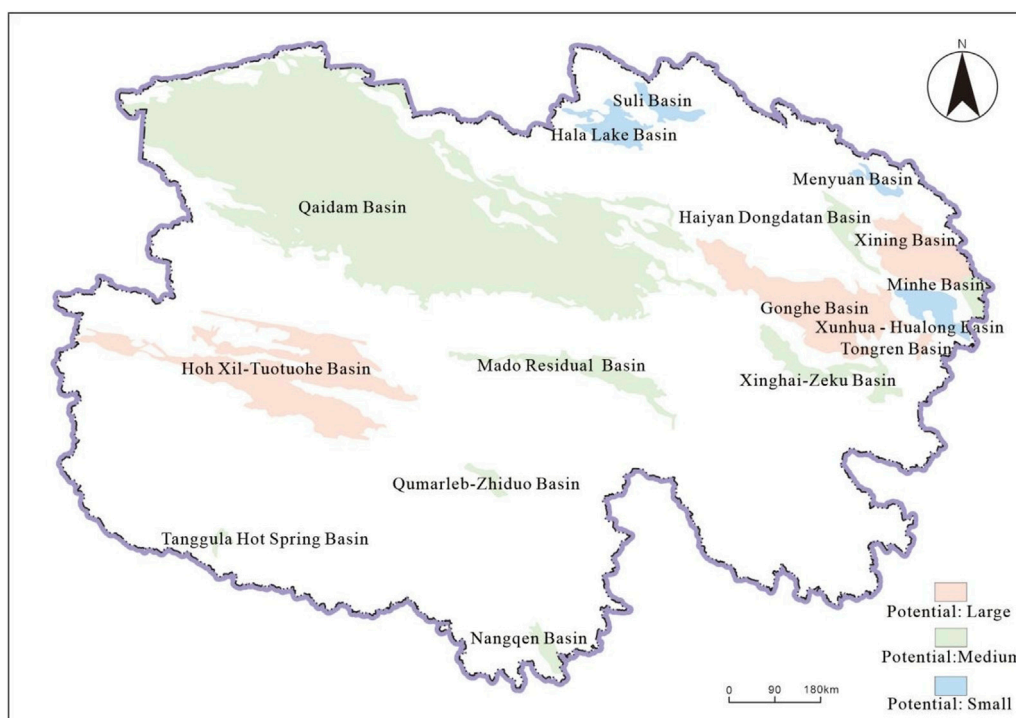


FIGURE 6 AHP geothermal resource potential zoning map.

TABLE 9 PCA comprehensive score table.

No.	Basin name	PCA comprehensive score	Potential
1	Gonghe Basin	1.325	Large
2	Hoh Xil-Tuotuohe Basin	0.626	
3	Tongren Basin	0.589	
4	Xining Basin	0.542	
5	Qaidam Basin	0.493	Medium
6	Minhe Basin	0.342	
7	Tanggula Hot Spring Basin	0.32	
8	Nangqen Basin	0.244	
9	Qumarleb-Zhiduo Basin	-0.221	
10	Haiyan Dongdatan Basin	-0.317	
11	Xinghai-Zeku Basin	-0.425	
12	Mado Residual Basin	-0.614	
13	Hala Lake Basin	-0.709	Small
14	Suli Basin	-0.709	
15	Menyuan Basin	-0.709	
16	Xunhua and Hualong Basin	-0.781	

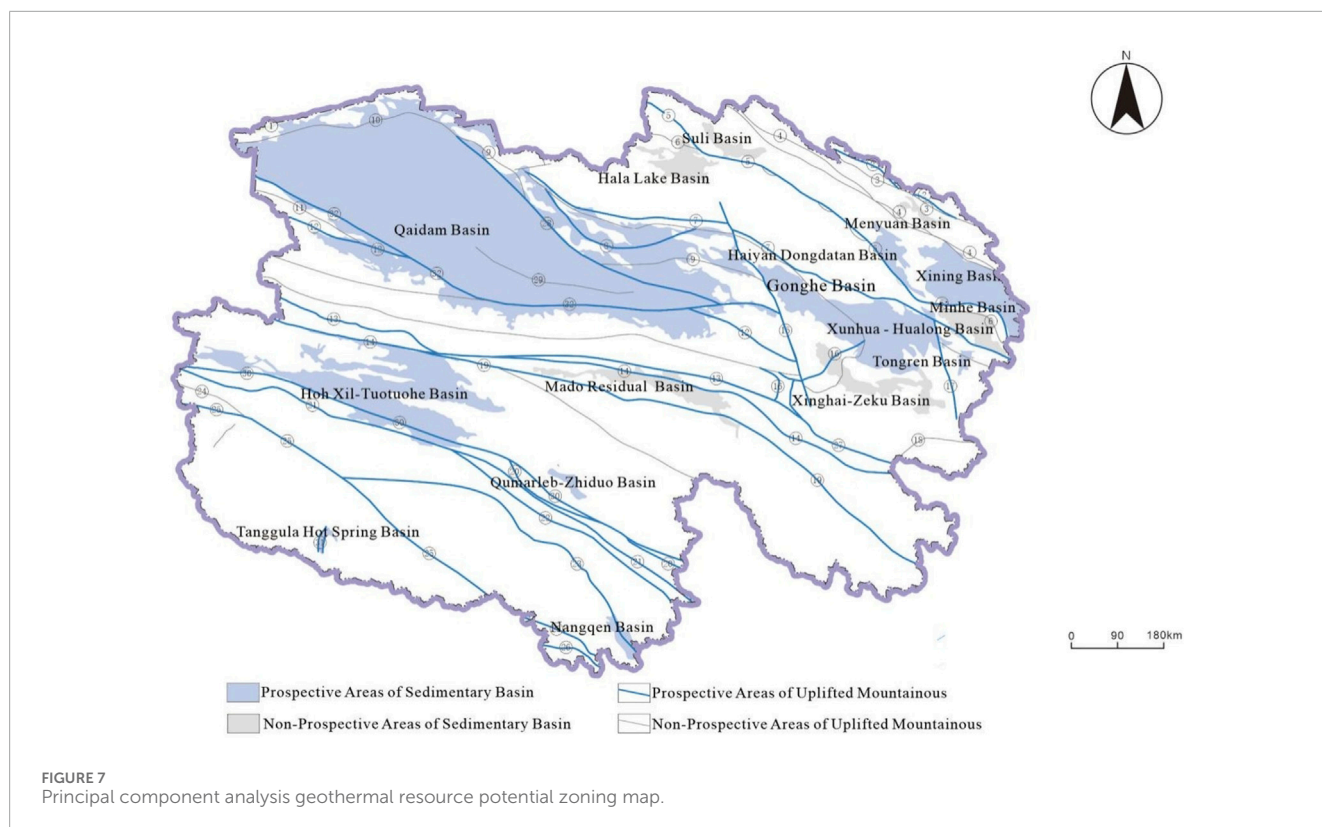


FIGURE 7 Principal component analysis geothermal resource potential zoning map.

TABLE 10 Basic parameter assignment table for evaluation indicators of potential uplifted mountainous area-type geothermal resources.

No.	Fault name	Cutting depth (km)	Length (km)	FZ width (m)	Average Spring temp. (°C)	No. of springs	Reservoir temp. (°C)	Activity history	Max Mag	Igneous rock %
1	F1 Allyn Tagh	80	250	500	13	1	20.8	Holocene	2.8	0.05
2	F2 Lenglongling N	80	320	250	15	3	24	Holocene	6.9	0.03
3	F3 Baoku River–Ebao	30	250	200	13	1	20.8	Himalayan	5.1	0.03
4	F4 Dabanshan N	80	116	200	13	1	20.8	Pre-Triassic	5.5	0.04
5	F6 Shulemanshan–Lajishan N	80	620	200	55	8	88	Pre-Triassic	3	0.08
6	F7 Lajishan S	80	150	200	14	1	22.4	Pre-Triassic	3	0.08
7	F8 Zongwulongshan–Qinghainan Shan	80	730	50	40	1	84	Late Triassic	3	0.15
8	F10 Olongbuluke N	80	230	10	15	1	24	Holocene	5.6	0.03
9	F11 Saishiteng–Wanggaixiu	5	283	50	12	1	19.2	Holocene	3.5	0.2
10	F12 Qaidam Basin N margin	5	250	50	12	1	19.2	Holocene	4.7	0.01
11	F14 Lianhuashi–Xiaolangyashan	5	127	50	11	1	17.6	Holocene	3.5	0.05
12	F15 Adatan–Wulanwuzhuèr S	80	340	500	12	1	19.2	Holocene	4.2	0.06
13	F18 Kunnan	80	1,000	200	18	1	28.8	Holocene	5.2	0.15
14	F19 Buqingshan S	70	800	1,000	39	1	62.4	Holocene	8	0.25
15	F20 Wahongshan–Wenquan	30	275	500	65	6	104	Late Triassic	2.8	0.4
16	F21 Wenquan–Qijia	5	200	100	62	1	99.2	Late Triassic	2.5	0.1
17	F23 Guide–Duohebao	5	120	50	70	3	112	Holocene	5.5	0.3
18	F24 Zequ–Tuoyema	5	68	80	12	1	19.2	Holocene	4.5	0.01
19	F25 Kumlunkou–Gande	30	780	600	50	1	80	Holocene	6.9	0.05

(Continued on the following page)

TABLE 10 (Continued) Basic parameter assignment table for evaluation indicators of potential uplifted mountainous area-type geothermal resources.

No.	Fault name	Cutting depth (km)	Length (km)	FZ width (m)	Average Spring temp. (°C)	No. of springs	Reservoir temp. (°C)	Activity history	Max Mag	Igneous rock %
20	F28 Dangi-jiang-Zhimenda	5	252	50	18	2	28.8	Holocene	5.4	0.03
21	F29 Xijir-Ulan North-Yushu	80	800	200	50	7	80	Himalayan	7.1	0.03
22	F30 Bamqu-Gela	5	137	300	35	4	56	Himalayan	5.2	0.03
23	F31 Wuli-Nangqen	5	560	200	30	5	48	Himalayan	4.2	0.01
24	F32 Wulanwula N margin-Jieduo	80	734	200	14	1	22.4	Himalayan	5.2	0.01
25	F33 Wulanwula S margin	80	100	200	50	4	80	Himalayan	5.2	0.08
26	F35 Tanggula S margin	80	100	500	55	1	88	Himalayan	4.7	0.15
27	Zhongtie fault	5	230	50	53	1	84.8	Holocene	4-5	0.01
28	Qaidam Basin N Central F	5	230	700	12	1	19.2	Holocene	5-6.8	0.01
29	Qaidam Basin S central F	5	190	300	12	1	19.2	Holocene	5	0.01
30	Wudaoliang-Qumartleb F	30	800	200	11	1	17.6	Holocene	6.5	0.01
31	Tanggula Hot Spring Basin F	5	34	100	68	3	108.8	Holocene	5.5	0.05
32	Mangya Youshashan F	80	200	200	85	1	136	Holocene	6.4	0.01

FZ, fracture zone; Mag, magnitude, temp., temperature.

TABLE 11 AHP evaluation results for potential uplifted mountainous area-type geothermal resources.

Rank	Fault name	AHP score	Potential
1	F23 Guide–Duohehao	77.4528	Large
2	F19 Buqingshan S	72.2674	
3	Mangya Youshashan F	68.5977	
4	F20 Wahongshan–Wenquan	62.9286	
5	Tanggula Hot Spring Basin F	62.2719	
6	F29 Xijir Ulan North–Yushu	60.7366	
7	F25 Kunlunkou–Gande	60.5245	
8	F35 Tanggula S margin	55.9498	
9	F33 Wulanwula S margin	53.5323	Medium
10	Zhongtie fault	49.9533	
11	F8 Zongwulongshan–Qinghainan Shan	46.4067	
12	F2 Lenglongling N	46.26	
13	F6 Shulenshan–Lajishan N	45.6081	
14	F18 Kunnan	44.9325	
15	F21 Wenquan–Qijia	44.6617	
16	F30 Bamqu–Gela	41.6556	
17	Qaidam Basin N Central F	40.9975	
18	F10 Olongbuluke N	40.1286	
19	F15 Adatan–Wulanwuzhu'er S	37.8005	
20	F28 Dangjiang–Zhimenda	37.625	
21	Wudaoliang–Qumarleb F	35.9066	
22	F11 Saishiteng–Wanggaixiu	35.7	
23	F31 Wuli–Nangqen	35.3938	
24	F4 Dabanshan N	33.4112	
25	Qaidam Basin S central F	32.7754	Small
26	F32 Wulanwula N Margin–Jieduo	32.644	
27	F3 Baoku River–Ebao	32.4583	
28	F12 Qaidam Basin N margin	29.9763	
29	F24 Zequ–Tuoyema	29.7934	
30	F1 Altyn Tagh	27.8403	

(Continued on the following page)

TABLE 11 (Continued) AHP evaluation results for potential uplifted mountainous area-type geothermal resources.

Rank	Fault name	AHP score	Potential
31	F7 Lajishan S	25.3187	
32	F14 Lianhuashi–Xiaolangyashan	23.4419	

was calculated, and all CR values were below the threshold of 0.1, indicating acceptable consistency in the expert judgments.

$$A = (a_{ij})_{n \times n}, a_{ij} > 0, a_{ji} = 1/a_{ij}, a_{ii} = 1,$$

(where a_{ij} represents the relative importance of indicator i compared to indicator j).

2. Calculation of weight vectors: The geometric mean w_i^* of each row of the judgment matrix was calculated, and the vector $w^* = (w_1^*, w_2^*, \dots, w_n^*)^T$ was normalized to obtain the weight vector w .

$$w_i = \frac{w_i^*}{\sum_{k=1}^n w_k^*},$$

where $w = (w_1, w_2, \dots, w_n)^T$. The vector w represents the weights of the respective indicators (Tables 3, 4).

3. Score calculation: The standardized values of each indicator were multiplied by their corresponding weights and then summed to obtain the AHP composite score for each potential zone. The zones were ranked from highest to lowest based on these scores, reflecting the relative quality of metallogenic conditions. This ranking serves as the basis for potential zonation.

3.3 Principal component analysis (PCA)

PCA reduces dimensionality by transforming multiple variables into a few uncorrelated principal components that reflect most of the information from the original variables, overcoming the limitations of single-indicator evaluation (Mielke et al., 2016; Pang et al., 2018; Zhang Y. et al., 2021). Specific steps are as follows:

1. Construction of the evaluation structure model: This is consistent with the AHP model.
2. Data standardization: The original matrix of m samples and n indicators was standardized to eliminate the influence of different measurement units.
3. Calculation of the correlation matrix and its eigenvalues: The correlation matrix R ($n \times n$ dimension) of the standardized data was computed. The eigenvalues λ_k of R (sorted in descending order: $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_n \geq 0$) and their

TABLE 12 PCA evaluation results for potential uplifted mountainous area-type geothermal resources.

Rank	Fault name	PCA score	Potential	
1	F19 Buqingshan S	1.278	Large	
2	F20 Wahongshan–Wenquan	0.8901		
3	F23 Guide–Duohehao	0.8797		
4	F25 Kunlunkou–Gande	0.8772		
5	F29 Xijir Ulan North–Yushu	0.8737		
6	Mangya Youshashan F	0.8558		
7	Tanggula Hot Spring Basin F	0.5913		
8	F35 Tanggula S margin	0.4707		
9	F6 Shulenshan–Lajishan N	0.4596		Medium
10	F33 Wulanwula S margin	0.3139		
11	Zhongtie fault	0.1017		
12	F21 Wenquan–Qijia	0.0527		
13	Qaidam Basin N Central F	0.0468		
14	F8 Zongwulongshan–Qinghainan Shan	0.0333		
15	F30 Bamqu–Gela	0.0009		
16	F18 Kunnan	−0.0186		
17	F31 Wuli–Nanggen	−0.0627		
18	F2 Lenglongling N	−0.0682		
19	F15 Adatan–Wulanwuzhu'er S	−0.2051		
20	Wudaoliang–Qumarleb F	−0.2647		
21	F32 Wulanwula N Margin–Jieduo	−0.3436		
22	F28 Dangjiang–Zhimenda	−0.4655		
23	Qaidam Basin S central F	−0.4681		
24	F10 Olongbuluke N	−0.4682	Small	
25	F1 Altyn Tagh	−0.5042		
26	F3 Baoku River–Ebao	−0.5085		
27	F4 Dabanshan N	−0.5158		
28	F11 Saishiteng–Wanggaixiu	−0.6181		
29	F12 Qaidam Basin N margin	−0.6997		
30	F7 Lajishan S	−0.7603		

(Continued on the following page)

TABLE 12 (Continued) PCA evaluation results for potential uplifted mountainous area-type geothermal resources.

Rank	Fault name	PCA score	Potential
31	F24 Zequ–Tuoyema	−0.7728	
32	F14 Lianhuashi–Xiaolangyashan	−0.9816	

corresponding eigenvectors u_k ($k = 1, 2, \dots, n$) were calculated.

4. Determination of principal components and calculation of weights: The variance contribution rate V_k and the cumulative contribution rate of the k th principal component F_k were calculated.

$$V_k = \frac{\lambda_k}{\sum_{i=1}^n \lambda_i}$$

Principal components were extracted based on the criterion of eigenvalues greater than 1 or a cumulative variance contribution rate exceeding 80%. For the basin-type and fault-zone-type evaluations, the first four principal components explained more than 76% and 83% of the original information, respectively (Tables 5, 6).

5. Calculation of principal component scores: The weights in PCA typically reflect the comprehensive influence of each original indicator on the principal components. The scores of each potential zone on the principal components were calculated and used as the basis for potential zonation.

3.4 Determination of potential zones and prospective areas

To intuitively differentiate potential levels without presupposing the data distribution, this study employed the quartile method to divide the assessment results of both the AHP and PCA into three potential levels: high, medium, and low. Ultimately, the intersection of areas classified as either “high” or “medium” level in the assessment results of both methods was identified as a prospective geothermal resource area, thereby increasing the reliability of the results.

4 Calculation results

4.1 Zoning of potential sedimentary basin conductive-type geothermal resources

Values were assigned to the 11 indicators based on the methods above (Table 7). Terrestrial heat flow data came from 98 data points from the national fourth edition heat flow database for the province (Jiang et al., 2016), 29 from literature, and 8 measured data points. Heat flow values range from 25.5 mW/m² to 157.1 mW/m², with an average of 69.8 ± 26.2 mW/m², higher than the Chinese continental average of 61.5 mW/m². The presence

TABLE 13 List of prospective geothermal resource areas in Qinghai Province.

No.	Type	Prospective area	Intersection count	Is it a prospective area?
1	Basin	Gonghe Basin	2	Yes
2		Qaidam Basin	2	Yes
3		Hoh Xil-Tuotuohe Basin	2	Yes
4		Xining Basin	2	Yes
5		Tongren Basin	2	Yes
6		Nangqen Basin	2	Yes
7		Tanggula Hot Spring Basin	2	Yes
8		Minhe Basin	2	Yes
9		Qumarleb-Zhiduo Basin	2	Yes
10		Menyuan Basin	1	No
11		Haiyan Dongdatan Basin	2	Yes
12		Xinghai-Zeku Basin	1	No
13		Hala Lake Basin	1	No
14		Mado Residual Basin	1	No
15	Fault	F23 Guide-Duohemao	2	Yes
16		F19 Buqingshan S	2	Yes
17		Mangya Youshashan F	2	Yes
18		F20 Wahongshan-Wenquan	2	Yes
19		Tanggula Hot Spring Basin F	2	Yes
20		F29 Xijir Ulan North-Yushu	2	Yes
21		F25 Kunlunkou-Gande	2	Yes
22		F35 Tanggula S margin	2	Yes
23		F33 Wulanwula S margin	2	Yes
24		Zhongtie fault	2	Yes
25		F8 Zongwulongshan-Qinghainan Shan	2	Yes
26		F2 Lenglongling N	2	Yes
27		F6 Shulenanshan-Lajishan N	2	Yes
28		F18 Kunnan	2	Yes
29		F21 Wenquan-Qijia	2	Yes
30		F30 Bamqu-Gela	2	Yes
31		Qaidam Basin N Central F	2	Yes
32		F10 Olongbuluke N	2	Yes

(Continued on the following page)

TABLE 13 (Continued) List of prospective geothermal resource areas in Qinghai Province.

No.	Type	Prospective area	Intersection count	Is it a prospective area?
33		F15 Adatan–Wulanwuzhu'er S	2	Yes
34		F28 Dangjiang–Zhimenda	2	Yes
35		Wudaoliang–Qumarleb F	2	Yes
36		F11 Saishiteng–Wanggaixiu	1	No
37		F31 Wuli–Nangqen	2	Yes
38		F4 Dabanshan N	1	No
39		F32 Wulanwula N Margin–Jieduo	1	No
40		Qaidam Basin S central F	1	No

"1" indicates an intersection in only one method; "2" indicates an intersection in both methods.

of low-velocity bodies at 20 km depth was determined based on seismic tomography, crustal velocity profiles, and artificial seismic data, identifying their presence under the Gonghe Basin, Qaidam Basin, and Hoh Xil–Tuotuohe Basin. Basement lithology was assigned based on actual exposure or regional geological data. Reservoir temperature is the average of measured values from geothermal wells or calculated values from geothermometers. Reservoir thickness was estimated based on drilling data or as 22% of basement depth. Reservoir lithology was assigned based on porosity development. Recoverable modulus was calculated as the recoverable resource amount divided by the basin area. Water richness grade was determined based on production test data or analogy. The number of geothermal fields was assigned based on the actual count of 25 fields identified from existing exploration projects.

4.1.1 AHP calculation results

Based on the distribution of AHP comprehensive scores, potential areas were divided using the quartile method: Gonghe Basin, Qaidam Basin, Hoh Xil–Tuotuohe Basin, and Xining Basin are large-potential areas; Tongren Basin, Nangqen Basin, Tanggula Hot Spring Basin, Minhe Basin, Qumarleb–Zhiduo Basin, Menyuan Basin, Haiyan Dongdatan Basin, and Hala Lake Basin are medium-potential areas; Suli Basin, Xinghai–Zeku Basin, Xunhua and Hualong Basin, and Mado Residual Basin are small-potential areas (Table 8; Figure 6).

4.1.2 PCA calculation results

The PCA results show: Gonghe Basin, Hoh Xil–Tuotuohe Basin, Tongren Basin, and Xining Basin are large-potential areas; Qaidam Basin, Minhe Basin, Tanggula Hot Spring Basin, Nangqen Basin, Qumarleb–Zhiduo Basin, Haiyan Dongdatan Basin, Xinghai–Zeku Basin, and Mado Residual Basin are medium-potential areas; Hala Lake Basin, Suli Basin, Menyuan Basin, and Xunhua and Hualong Basin are small-potential areas (Table 9; Figure 7).

4.2 Zoning of potential uplifted mountainous area convective-type geothermal resources

For assigning values to the indicators for the uplifted mountainous area type, fault cutting depth, extension length, and fracture zone width were determined based on geological records, tectonic maps, active fault studies, and exploration reports. Spring count, temperature, and reservoir temperature are based on the latest survey results and previous data. Fault activity history was assigned based on provincial data and categorized into pre-Triassic, Late Triassic, Himalayan, Late Pleistocene, and Holocene. Earthquake magnitude is based on seismic network data. Igneous rock proportion was determined from regional geological maps (Table 10).

4.2.1 AHP calculation results

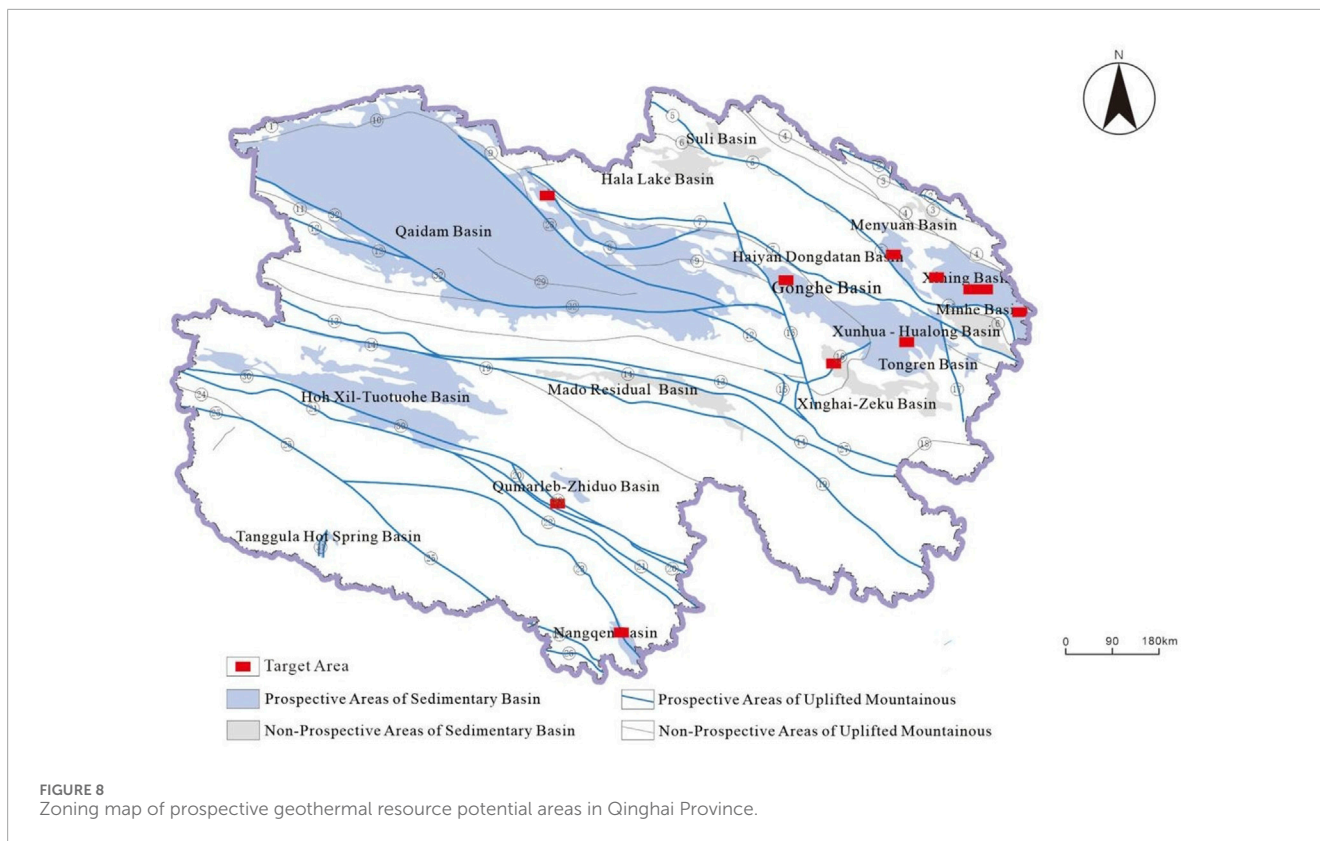
The AHP comprehensive evaluation results were divided using the quartile method: areas ranked 1–8 are large-potential areas, 9–24 are medium, and 25–32 are small (Table 11).

4.2.2 PCA calculation results

The PCA results were also divided using the quartile method: areas ranked 1–8 are large-potential areas, 9–24 are medium, and 25–32 are small (Table 12).

4.3 Delineation of geothermal resource prospective areas

Based on the evaluation results of the two resource types, the analytic hierarchy process (AHP) delineated 36 prospective areas (12 sedimentary basins and 24 faults), while principal component analysis (PCA) also identified 36 prospective areas (12 sedimentary basins and 24 faults). By taking the intersection of the results from both methods, a total of 32 geothermal resource prospective areas were ultimately delineated across the province. Among these, 10 are sedimentary basin conductive types, and 22 are mountainous uplift convective types (Table 13; Figure 8).



5 Discussion

5.1 Methodological discussion and comparison

The AHP-PCA combined method employed in this study effectively integrates expert knowledge with the objective patterns within the data. The AHP results place greater emphasis on control factors deemed critical by experts (e.g., terrestrial heat flow and fault activity). In contrast, the PCA results more comprehensively reflect the integrated statistical characteristics of all indicators. The intersection of results from both methods increases the reliability of the delineated prospective areas. Compared with previous evaluations in Qinghai Province, which primarily focused on resource quantity estimation, the “genetic factors–multi-indicator–semi-quantitative” system established in this study better reveals the controlling mechanisms and spatial variations governing resource occurrence, providing more direct evidence for target area prioritization.

5.2 Relationship between fault structures and geothermal manifestations

In-depth analysis of the spatial relationship between hot springs and faults indicates that high-temperature, high-flow geothermal manifestations are often not located directly on regional major faults. Instead, they are more commonly found where secondary faults have developed or at intersections of faults with different

orientations (e.g., the Guide–Duohe fault zone). These locations typically feature highly fractured rock with good permeability, which is more conducive to the rapid upflow of deep thermal fluids. In contrast, some large-scale but structurally simple major faults (e.g., the Altyn Tagh Fault F1) show less significant geothermal manifestations.

5.3 Target area prioritization

From the 32 delineated prospective areas, 10 exploration target areas were further prioritized (Figure 9; Table 14). The prioritization process systematically considered the following factors in addition to the resource potential assessment: 1. Location and infrastructure: Prioritizing areas near population and economic centers, such as towns with convenient transportation access. 2. Local demand: Aligning with Qinghai Province’s “Dual Carbon” goals and clean energy industry development plans, prioritizing regions with strong local demand. 3. Preliminary environmental screening: Avoiding environmentally sensitive areas like ecological conservation red lines.

5.4 Study limitations and future prospects

The evaluation system established in this study has been successfully applied within the specific geological context of Qinghai Province. However, its direct application to other regions with significantly different tectonic settings may require adjustments

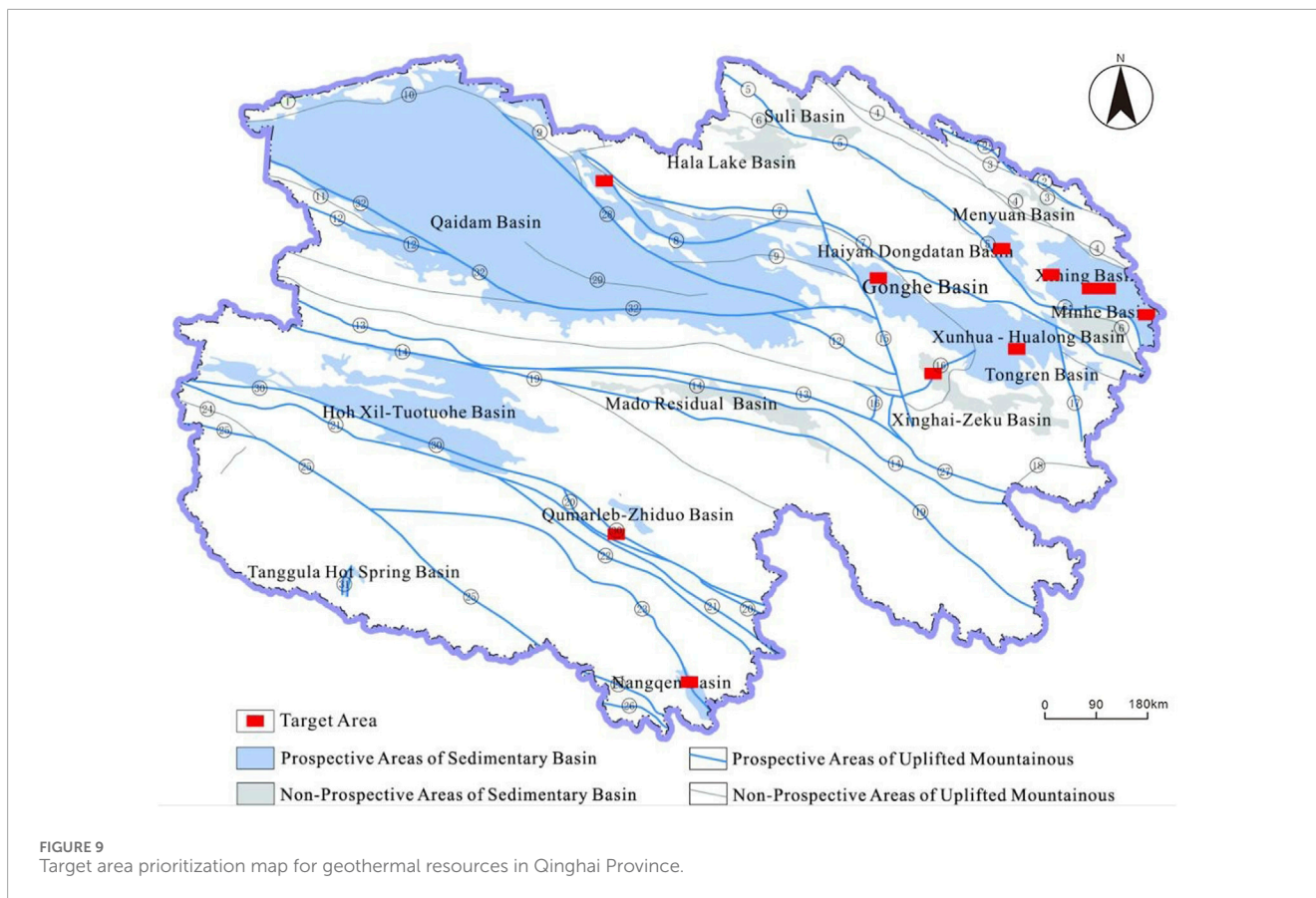


TABLE 14 List of optimized geothermal resource target areas in Qinghai Province.

No.	Region	Target area name	Associated geothermal resource prospective area
1	Xining	Huangzhong District, Lushar Town	Xining Basin and Lajishan north margin fault zone
2	Haidong	Minhe County, Bazhou Town	Minhe Basin and Lajishan north margin fault zone
3		Ping'an-Ledu area	Xining Basin, Minhe Basin, and Lajishan north margin fault zone
4	Haibei	Haiyan County, Xihai Town	Haiyan Basin
5	Hainan	Guinan County, Shagou Township	Gonghe Basin
6		Xinghai County, Ziketang Town	Wahongshan-Wenquan FZ and Wenquan-Qijia FZ
7	Haixi	Da Qaidam Town	Qaidam Basin and Zongwulong-Qinghainan Shan FZ
8		Ulan County, Chaka Town	Gonghe Basin
9	Yushu	Nangqen County, Xiangda Town	Nangqen Basin and Wuli-Nangqen FZ
10		Zhiduo County, Jiajiboluo Town	Qumarleb-Zhiduo Basin

to the evaluation indicators and their weights. Future research could explore the following directions: 1. validating and calibrating this evaluation system in other typical geothermal regions; 2.

incorporating reservoir numerical simulation to dynamically assess resource extraction potential; 3. integrating full lifecycle economic cost and environmental impact assessments more deeply

into the target area decision-making model. The development of geothermal resources must focus on sustainability. Future detailed exploration stages require targeted evaluations of reservoir sustainable exploitation potential and environmental monitoring (e.g., handling of high-salinity fluids, monitoring of induced seismicity, etc.).

6 Conclusion

Qinghai Province boasts abundant geothermal resources with substantial reserves. There are 91 natural hot spring outcrops and 84 geothermal anomaly wells. The total mid-to-deep geothermal energy resource is estimated at 475.754 billion tons of standard coal equivalent, with an extractable resource of 47.5754 billion tons. Based on hydrodynamic conditions, geological structure, and heat conduction characteristics, the hydrothermal resources are classified into two types: sedimentary basin conductive type and mountainous uplift convective type.

This study applies the analytic hierarchy process (AHP) and principal component analysis (PCA) to assess the potential of hydrothermal resources in Qinghai Province. Moving beyond the traditional “follow the heat” approach, it adopts a “Source–Pathway–Cap–Reservoir–Fluid” element framework. Utilizing 11 evaluation indicators for basins and 9 for fault zones, a semi-quantitative assessment was conducted for 16 sedimentary basins and 32 fault zones. This established a multi-factor, semi-quantitative evaluation system, providing a scientific basis for prioritizing exploration targets and effectively reducing exploration risks.

By integrating the evaluation results from both methods, 32 geothermal resource prospective areas were delineated across the province. Comprehensively considering resource potential, locational conditions, and development needs, 10 target areas suitable for further near-term exploration were prioritized. This offers clear scientific guidance for the exploration and development planning of geothermal resources in Qinghai.

The evaluation framework proposed in this study holds methodological significance and can serve as a reference for similar work in other regions, although its specific application requires adjustments based on local geothermal geological conditions. Advancing the exploration and sustainable development of geothermal resources necessitates collaborative innovation across multiple fields, including resource assessment, engineering technology, and environmental management.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding authors.

Author contributions

WX: Formal analysis, Data curation, Writing – original draft, Writing – review and editing, Investigation. RL: Supervision,

Writing – review and editing, Conceptualization, Investigation, Methodology, Funding acquisition, Project administration, Resources, Writing – original draft, Formal analysis. BL: Formal analysis, Validation, Conceptualization, Methodology, Writing – review and editing. JZ: Writing – original draft, Supervision, Conceptualization, Investigation. JC: Methodology, Investigation, Writing – original draft, Visualization, Formal analysis. DZ: Writing – review and editing, Validation, Investigation, Data curation, Formal analysis. XW: Visualization, Writing – original draft, Data curation, Software.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This study was supported by the Qinghai Province Clean Energy Minerals Special Project (Nos 2022013004qj004 and 2023086020qj002).

Acknowledgements

The authors extend their sincere gratitude to the experts who generously gave their time and expertise to this study and its publication.

Conflict of interest

Authors WX, RL, BL, JZ, and XW were employed by the Qinghai Geological Survey Bureau.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

- Abdi, H., and Williams, L. J. (2010). Principal component analysis. *Wiley Interdiscip. Rev. Comput. Stat.* 2, 433–459. doi:10.1002/wics.101
- Chen, L., Jiang, G., Hu, J., Liu, Y., Xi, Y., and Lei, H. (2025). Optimization of hot dry rock heat extraction considering multi-mineral reactions and fracture roughness under THMC coupling. *Renew. Energy* 218, 119234. doi:10.1016/j.renene.2025.119234
- Du, H., Jiang, Y., Yan, Z., Guo, F., and Zhu, B. (2011). Sedimentary characteristics and environmental analysis of the Paleogene nangqian basin, Qinghai province. *Acta Geol. Sin.* 85, 383–395. doi:10.3969/j.issn.0001-5717.2011.03.009
- He, D., Ren, L., Hao, J., Li, J., Zhang, H., and Zhang, Y. (2023). Research on geothermal resource evaluation system based on analytic hierarchy process: a case study of mid-deep sandstone reservoir of hydrothermal geothermal resource in Caofeidian area, Hebei Province. *Reserv. Eval. Dev.* 13, 713–725. doi:10.13809/j.cnki.cn32-1825/te.2023.06.007
- Hu, S., Huang, S., He, L., and Wang, J. (2013). Lithospheric thermal structure and geothermal resource potential in the continental area of China. *Acta Geol. Sin.* 87 (S1), 36. doi:10.3969/j.issn.0001-5717.2013.z1.007
- Jiang, G., Gao, P., Rao, S., Zhang, L., Tang, X., Huang, F., et al. (2016). Compilation of heat flow data in the continental area of China (4th edition). *Chin. J. Geophys.* 59, 2892–2910. doi:10.6038/cjg20160815
- Li, Y., Zhu, L., Dai, J., Wang, C., and Wu, Z. (2013). Sedimentary and tectonic characteristics of the yanghu basin in the Western hoh xil area and their dynamic implications. *Acta Petrol. Sin.* 29, 1017–1026. doi:10.3969/j.issn.1000-0569.2013.03.015
- Li, J., Li, Q., Shao, W., Li, M., Ye, B., Su, P., et al. (2025). Hydrogeochemical characteristics of hot spring water in the weixi-qiaohou fault zone. *Earthquake* 45 (2), 115–127. doi:10.12196/j.issn.1000-3274.2025.02.009
- Li, X., Wang, G., Zhang, S., and Zhang, X. (2025). Thermo-hydro-mechanical coupling analysis of spiral wellbores for enhanced heat extraction in the gonghe basin, China. *Geothermics* 117, 102891. doi:10.1016/j.geothermics.2024.102891
- Lin, W., Liu, Z., Wang, W., and Wen, M. (2013). Assessment of geothermal resources and potential in China. *Chin. Geol.* 40, 312–321. doi:10.3969/j.issn.1000-3657.2013.01.022
- Lin, W., Gan, H., Zhao, Z., Zhang, W., and Liao, Z. (2023). Lithospheric thermal-rheological structure of the gonghe basin and its geothermal implications. *Acta Geosci. Sin.* 44, 45–56. doi:10.3975/cagsb.2023.122001
- Liu, S., Luo, X., Gu, P., Li, X., Zhang, L., and Li, F. (2024). Deep tectonic framework of the gonghe basin and its influence on the heat source of hot dry rock. *Northwest. Geol.* 57, 130–141. doi:10.12401/j.nwg.20240409
- Lu, R., Xie, W., and Liu, B. (2024). *Research report on geothermal resource potential evaluation and development direction in Qinghai province*. Xining, China: Qinghai Geological Survey. Available online at: http://www.qhdzd.com.cn/xxgk/tzgg/202405/t20240516_123456.html.
- Mielke, P., Bär, K., and Sass, I. (2016). Principal component analysis for the assessment of deep geothermal resources: a case study from the molasse basin, Germany. *Renew. Energy* 97, 186–195. doi:10.1016/j.renene.2016.05.005
- Natural Resources and Territory Spatial Planning (2011). *Geologic exploration standard of geothermal resources: gb/t 11615–2010*. Beijing: Standards Press of China. Available online at: <https://std.samr.gov.cn/gb/search/gbDetailed?id=71F772D82D16D3A7E05397BE0A0AB82A>.
- Natural Resources and Territory Spatial Planning (2020). *Specification for estimation and evaluation of geothermal resources: dz/t 0331–2020*. Beijing: Geology Press. Available online at: http://gm.mnr.gov.cn/202011/t20201127_2591490.html.
- Pang, Z., Luo, J., Cheng, Y., and He, L. (2018). Assessment of geothermal resource potential in sedimentary basins of China based on principal component analysis. *Chin. J. Geophys.* 61, 4117–4129. doi:10.6038/cjg2018L0725
- Pang, Z., Luo, J., Cheng, Y., Duan, Z., He, L., and Li, Y. (2020). Evaluation of geological conditions for deep geothermal energy exploitation in China. *Earth Sci. Front.* 27, 134–151. doi:10.13745/j.esf.2020.1.15
- Qiu, N., Hu, S., and He, L. (2019). *Geothermics of sedimentary basins*. Dongying: China University of Petroleum Press. doi:10.3969/j.issn.1000-3754.2019.05.001
- Qiu, N., Tang, B., and Zhu, C. (2022). Deep thermal background of hot spring distribution in the Chinese continent. *Acta Geol. Sin.* 96, 195–207. doi:10.3969/j.issn.0001-5717.2022.01.015
- Saaty, T. L. (1990). How to make a decision: the analytic hierarchy process. *Eur. J. Oper. Res.* 48, 9–26. doi:10.1016/0377-2217(90)90057-I
- Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *Int. J. Serv. Sci.* 1, 83–98. doi:10.1504/IJSSCI.2008.017590
- Song, C., Fang, X., Li, J., Gao, J., and Liu, D. (2003). Late Cenozoic sedimentary evolution of the guide basin and uplift of the northern Tibetan Plateau. *Geol. Rev.* 49, 337–346. doi:10.3321/j.issn.0371-5736.2003.04.002
- Tang, X., Wang, G., Ma, Y., Zhang, D., and Yan, Y. (2020). Heat source mechanism and thermal accumulation model of geothermal resources in the gonghe basin, Qinghai, China. *Acta Geol. Sin.* 94, 2052–2065. doi:10.3969/j.issn.0001-5717.2020.07.009
- Tang, X., Wang, G., Zhang, D., Yan, Y., and Li, J. (2023). Active tectonics and formation mechanism of the high-temperature thermal anomaly in the gonghe basin, northeastern Tibetan Plateau. *Acta Geosci. Sin.* 44, 7–20. doi:10.3975/cagsb.2023.120801
- Technical Committee on Standardization of Geothermal Energy of the Energy Industry (2020). *Evaluating methods of geothermal reservoirs: NB/T 10263–2019*. Beijing: China Petrochemical Press. Available online at: http://www.nea.gov.cn/2020-06/30/c_139177436.htm.
- Technical Committee on Standardization of Geothermal Energy of the Energy Industry (2021). *Classification and assessment methods for geothermal resources/reserves: NB/T 10700–2021*. Beijing: China Petrochemical Press. Available online at: http://www.nea.gov.cn/2021-12/22/c_1310403996.htm.
- Vaidya, O. S., and Kumar, S. (2006). Analytic hierarchy process: an overview of applications. *Eur. J. Oper. Res.* 169, 1–29. doi:10.1016/j.ejor.2004.04.028
- Wang, J., and Gong, Y. (2017). The role of geothermal energy in the establishment of a clean and low-carbon energy system. *Bull. Chin. Acad. Sci.* 32, 1224–1230. doi:10.16418/j.issn.1000-3045.2017.11.009
- Wang, G., Zhang, W., Liang, J., Zhang, L., and Liu, Z. (2017). Evaluation of geothermal resources potential in China. *Acta Geosci. Sin.* 38, 449–459. doi:10.3975/cagsb.2017.04.02
- Wang, A., Sun, Z., Lin, W., Yang, N., Ye, H., Tong, J., et al. (2024). Occurrence characteristics and potential evaluation of geothermal resources in Jiangxi province. *Chin. Geol.* doi:10.12029/gc20230217002
- Yang, S., Luo, Y., and Zhao, Z. (2015). *Current situation evaluation and zoning report of geothermal resources in Qinghai province*. Xining, China: Qinghai Bureau of Environmental Geology Exploration. Available online at: <http://www.qheg.com.cn/plus/view.php?aid=152>.
- Yun, X., Chen, X., Cai, Z., Li, J., Zhang, S., and Li, J. (2020). A preliminary study on the magma emplacement, crystallization conditions and deep structure of dry-hot rock in the northeastern gonghe basin, Qinghai province. *Acta Petrol. Sin.* 36, 3171–3191. doi:10.18654/1000-0569/2020.10.15
- Zhang, C. (2022). Suitability evaluation of shallow geothermal energy based on AHP-Fuzzy comprehensive evaluation model: a case study of changle county, Shandong Province. *Geol. Surv. China* 9, 91–99. doi:10.19388/j.zgdzdc.2022.02.01
- Zhang, C., Hu, S., Song, R., Liu, S., Zhang, S., and Li, X. (2020). Genetic mechanism of the enhanced geothermal system in the gonghe basin: constraints from radiogenic heat production from rocks. *Chin. J. Geophys.* 63, 2697–2709. doi:10.6038/cjg2020N0159
- Zhang, Q., Xie, M., and Xue, C. (1992). Statistical analysis of tectonic evolution in the Western qaidam basin, Qinghai. *Sci. Geol. Sin.* (1), 168–176. Available online at: https://kns.cnki.net/kcms2/article/abstract?v=OLEU9YGvHk1AiY0f_2qbpVpmOz0oM1GmRt-f6XlvTNjw1NwP7FuHxU0Wq8jFqtxHn43wxYoLASNKJmBXBO_uW1BOJ3ufQm36Qz78kGRSUpdcbwN7Rchle-Vv_4C7Fsm6Q4b_W0DZ9pkHwX-GFRrmQAwTyNHs9C6H7qOAmMeVt33Cesq_c3H8A==&uniplatform=NZKPT&language=CHSW CNKI.
- Zhang, S., Zhang, L., and Li, J. (2015). *Special research report on geothermal resources exploration, development and utilization planning in Qinghai province*. Xining, China: Qinghai Hydrogeology, Engineering Geology and Environmental Geology Survey Institute. Available online at: <http://www.qhsdy.com.cn/News/View.asp?ID=178>.
- Zhang, L., Li, X., Zhu, G., Li, J., Li, F., and Zhang, S. (2024). Temperature field characteristics, genesis and resource potential of hot dry rock in the gonghe basin, Qinghai province. *Chin. Geol.* doi:10.12029/gc20240315001
- Zhang, Y., Li, Y., Liu, F., Zheng, G., Liu, C., and Zhang, W. (2025). The source and differential enrichment mechanisms of lithium in gudui geothermal field, Tibetan Plateau. *Appl. Geochem.* 166, 105952. doi:10.1016/j.apgeochem.2024.105952
- Zhang, S., Wu, H., Zhang, Y., Li, X., Wang, G., and Qi, J. (2020). Geology and geothermics of the guide county hot-dry rock in Qinghai province. *Acta Geol. Sin.* 94, 1591–1605. doi:10.3969/j.issn.0001-5717.2020.05.012
- Zhang, S., Li, X., Song, J., Li, J., Zhao, X., and Zhang, C. (2021). Geophysical evidence for the existence of intracrustal partial melting layer and analysis of regional heat source for hot dry rock resources in gonghe basin. *Earth Sci.* 46, 1416–1436. doi:10.3799/dqkx.2020.238

Zhang, Y., Xu, M., Wang, Z., and Pang, Z. (2021). Assessment of geothermal resources potential in Guangdong province, China based on PCA and fuzzy comprehensive evaluation. *Geothermics* 96, 102219. doi:10.1016/j.geothermics.2021.102219

Zhou, B. (2007). *Distribution characteristics of active faults in Qinghai province and their harm to highway engineering*. Master's thesis (Chang'an University). Available online at: <https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CMFD&dbname=CMFD2007&filename=2007089939.nh>.

Zhou, X., Wang, W., Li, L., Du, J., and Liu, L. (2020). Geochemical characteristics of gas from hot springs in the jinshajiang-red river fault zone. *Acta Petrol. Sin.* 36, 2197–2214. doi:10.18654/1000-0569/2020.07.18

Zhu, X., Wang, G., Ma, F., Lin, W., Zhang, W., Zhang, B., et al. (2024). Assessment of geothermal resource potential in the Xiong'an new area. *Earth Sci.* doi:10.3799/dqkx.2022.242

Zou, H., Hastie, T., and Tibshirani, R. (2006). Sparse principal component analysis. *J. Comput. Graph. Stat.* 15, 265–286. doi:10.1198/106186006X113430