

Article

Geothermal System Elements and Genetic Mechanism of High-Temperature Geothermal Resources in the Changbai Mountain Area

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Abstract

The Changbai Mountain area, the largest Cenozoic intraplate volcanic field in eastern China, features abundant high-temperature hot springs and high geothermal potential. However, the genesis and aggregation patterns of its geothermal systems remain poorly understood. This study recalculates crustal and residual deep/mantle heat-flow components along a representative profile and synthesizes published geological, geophysical, geochemical, and geothermal evidence to characterize the main geothermal system elements, including caprock, reservoirs, water source, and migration pathways. Controlling factors are examined from three dimensions: deep dynamics, magmatic heat source, and fault characteristics. Results reveal a “Cold crust–Hot mantle” thermal structure. The heat-flow calculation indicates that crustal radiogenic heat contributes approximately 40% of the surface heat flow, implying a dominant deep heat contribution. The available evidence suggests the presence of potential hydrothermal reservoirs in carbonate and clastic rocks, possible HDR targets in deeper metamorphic rocks, and locally effective basaltic sealing units. Fault systems and meteoric recharge likely control fluid circulation. Geothermal systems are controlled by mantle upwelling and lithospheric thinning due to western Pacific Plate subduction, multi-source heat coupling, effective caprock sealing, and fault-controlled water–heat conduction. These results provide a conceptual framework for future geothermal exploration and testing. This study elucidates the aggregation patterns and genetic mechanisms, providing a theoretical basis for exploration and development.

Keywords: the Changbai Mountain; high-temperature geothermal resource; geothermal system; magma chamber system; genetic mechanism



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1. Introduction

Geothermal energy, as a clean, stable, and renewable baseload energy source, is receiving increasing attention in the global energy transition. High-temperature geothermal systems can not only provide stable heat sources for power generation but also offer integrated support for district heating, hot spring therapy, and other industries, delivering substantial economic benefits and environmental value. China is a major geothermal resource country. According to data released at the 2023 World Geothermal Congress, China’s installed capacity for geothermal direct use accounts for 57.8% of the global total, and the utilized thermal energy accounts for 56.1% of the world’s total; both shallow

and medium-deep geothermal direct use rank first globally in scale [1]. However, in contrast to its world-leading position in direct use, China's high-temperature geothermal utilization, primarily for power generation, lags behind significantly. High-temperature geothermal resources in China have traditionally been considered to be concentrated in regions such as Tibet and Yunnan in the southwest. Yet, these areas have low population and economic density, making long-distance transmission of geothermal power to the east prohibitively expensive and severely constraining large-scale development and utilization. Consequently, researchers have turned their attention to the circum-Pacific geothermal belt in eastern China [2–4]. The Changbai Mountain area, as the largest active volcanic system in Northeast China, features numerous high-temperature hot springs and is regarded as one of the most promising high-temperature geothermal resource areas in eastern China [5–7]. Nevertheless, compared with the Qinghai–Tibet Plateau and the Tengchong area, research on high-temperature geothermal systems in Changbai Mountain remains relatively limited, and a systematic understanding of the spatial aggregation patterns and genetic mechanisms of geothermal resources is still lacking. This knowledge gap not only impedes science-based decision-making for geothermal resource exploration and development but also represents a weak link in understanding the formation mechanisms of intraplate geothermal systems.

In recent years, a series of exploratory studies have been conducted on geothermal resources in the Changbai Mountain area, laying a foundation for further research. Regarding geothermal resource distribution, previous studies integrating numerical simulations, machine learning, borehole measurements, and Curie depth constraints have estimated the terrestrial heat flow in this area to range from approximately 70 to 270 mW/m², significantly higher than the average heat flow of continental China, indicating substantial potential for high-temperature geothermal power generation [8–13]. Similar studies have demonstrated that subsurface heat transfer and temperature evolution are strongly governed by geological media properties and thermal transport mechanisms [14]. In terms of deep structure, geophysical methods such as seismic velocity, magnetotelluric sounding, and gravity surveys have revealed the presence of low-velocity and low-resistivity anomalies in the crust and upper mantle beneath the Changbai Mountain area, which are associated with the volcanic magmatic system. These anomalies have been interpreted as a magma chamber system, the origin of which is closely linked to the subduction of the Western Pacific Plate [15–19]. In geochemical studies, ion and gas component analyses combined with geochemical geothermometers have been used to estimate reservoir temperatures in the area, providing important constraints for investigating the genesis of high-temperature geothermal systems [6,20–24]. These studies have revealed certain characteristics of the high-temperature geothermal system in Changbai Mountain from different perspectives; however, they predominantly focus on individual factors and have not yet holistically addressed the core issue of how these high-temperature geothermal systems are spatially aggregated and genetically formed in this region.

Based on the above research background and core questions, this study focuses on the high-temperature geothermal system in the Changbai Mountain area. By integrating regional geological structural analysis, geophysical survey data, geothermal fluid geochemical data, and existing geothermal resource results, the research is carried out from the following three aspects. First, based on the regional geological characteristics and geothermal resource features of the Changbai Mountain area, we analyze and summarize the characteristics of the key elements of the high-temperature geothermal system (heat source, water source, reservoir, pathway, and cap rock). Second, from the three dimensions of magmatic heat source conditions, fault structural framework, and deep thermal structure, we examine the genetic controlling factors of high-temperature geothermal accumulation. Finally, integrating the above analyses, we construct a genetic model for the accumulation

of the high-temperature geothermal system in the Changbai Mountain area and explore the coupling mechanisms of different controlling factors in the geothermal accumulation process. This study aims to deepen the theoretical understanding of the formation mechanism of the intraplate high-temperature geothermal system in Changbai Mountain and to provide a geological basis for the scientific exploration and efficient development of regional geothermal resources.

2. Geological Settings

2.1. Regional Geological Settings

The Changbai Mountain area is located on the China–North Korea border in eastern Jilin Province, Northeast China. It is the largest Cenozoic intraplate volcanic region in eastern China and a typical example of arc-rear volcanism in the Western Pacific subduction zone, covering an area of approximately 20,000 km² (Figure 1). Tectonically, it lies on the northeastern margin of the North China Craton, within an arc-rear extensional setting of the Western Pacific subduction zone. It is adjacent to the Songliao Basin to the west and faces the Japan Sea back-arc basin to the east. The Changbai Mountain volcanoes are intraplate volcanoes [25,26] and consist of extensive lava plateaus, numerous volcanic craters, and three main eruption centers: the Tianchi volcano, the Wangtian’e volcano, and the Nanbaotai volcano. Among them, the Tianchi volcano is the largest Late Cenozoic central-eruption composite stratovolcano in China [27,28]. This region has experienced a long and complex geological evolution, characterized by intense tectonic deformation and strong magmatic activity. The widespread volcanic cover and dense fault network together constitute the basic geological setting for the formation and accumulation of the high-temperature geothermal system.

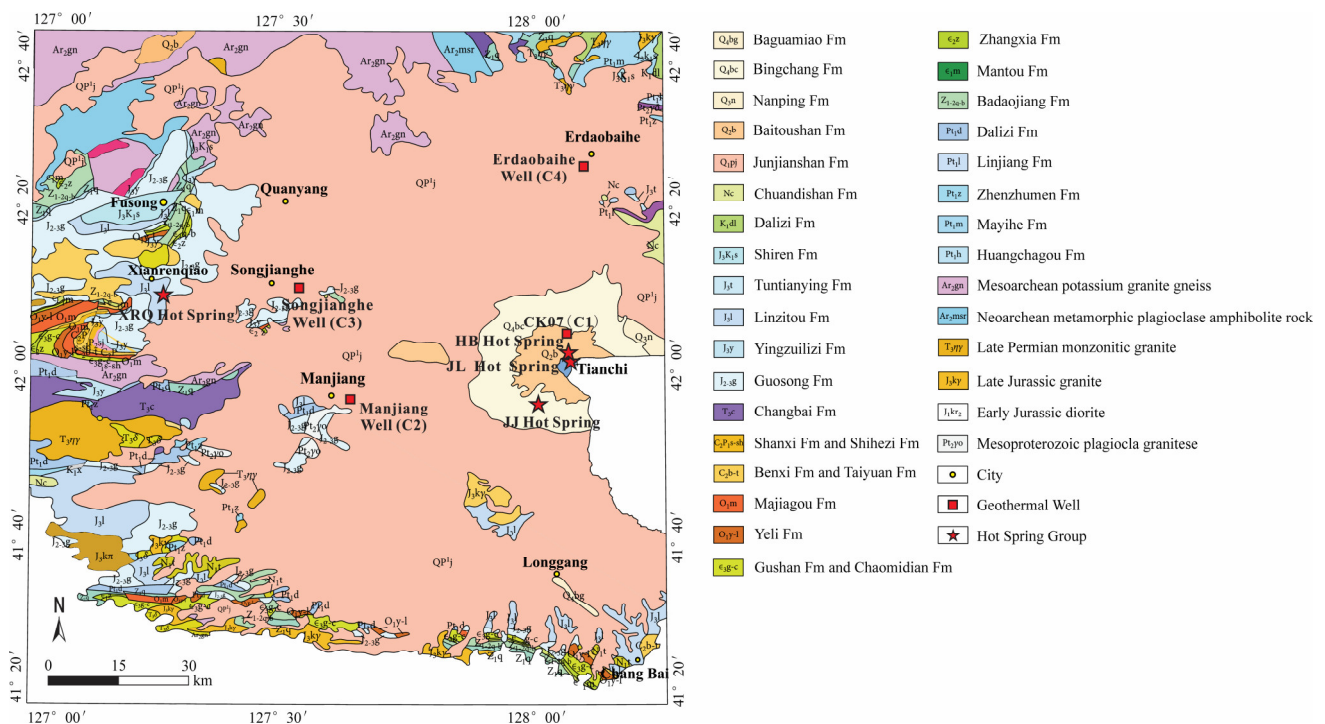


Figure 1. Geological map of the Changbai Mountain area [22].

The stratigraphy of the Changbai Mountain area is relatively complete, ranging from the Archean to the Cenozoic, with the most widespread distribution being Cenozoic volcanic rocks. The basement of the area consists of Archean to Middle–Late Proterozoic metamorphic rocks and Mesozoic granites [22–30]. Above the basement, the Paleozoic

succession includes the Sinian (Ediacaran), Cambrian, Ordovician, Carboniferous, and Permian strata, with well-developed carbonate rocks. The Mesozoic strata are mainly sandstones and conglomerates. The Cenozoic strata are the most widely distributed and thickest stratigraphic unit in the region, with extensive basalt cover forming the dominant lithology at the surface. The Cenozoic strata consist mainly of products from multiple volcanic eruptions, including Miocene to Pliocene basalt plateaus, Early Pleistocene basalt highlands, and Middle–Late Pleistocene to Holocene volcanic cone deposits.

2.2. Tectonic Evolution Characteristics

Late Cenozoic volcanism is extensively developed in Northeast China, widely distributed along rift basins and ridge belts surrounding the Songliao Basin [27,31–35], forming renowned volcanic fields such as Changbai Mountain, Longgang, Jingpohu, and Wudalianchi. The formation of Changbai Mountain is intimately linked to the subduction of the Pacific Plate beneath the Eurasian Plate [36]. This stagnant slab and overlying mantle wedge provide the geodynamic framework for asthenospheric upwelling, partial melting, and enhanced mantle heat flow beneath Changbai Mountain. Since the Cenozoic, the Pacific Plate has undergone significant tectonic evolution: from 55 to 25 Ma, it subducted at a low angle; from 25 to 15 Ma, trench retreat and slab rollback occurred; since 15 Ma, the Pacific Plate has descended into the mantle transition zone, eventually reaching its bottom, forming a thickened and flattened stagnant slab and a large mantle wedge above it [37].

The formation and evolution of Changbai Mountain can be divided into three main stages: shield-building, cone-building, and caldera-forming [38–40]. Since the Early Miocene, multiple episodes of basaltic eruption have occurred in the area, including: the Miocene pre-shield-building stage (22.6–10.4 Ma), characterized by limited outcrop distribution and ambiguous genesis; the Pliocene to Early Pleistocene shield-building stage, represented by eruptions at Tianchi, Wangtian’e, and Nanbaotai volcanoes, with Tianchi activity concentrated at 5.02–1.05 Ma and Wangtian’e at 4.77–1.86 Ma, contributing the largest volume of basaltic eruptive products; and the Middle–Late Pleistocene post-shield-building stage (1.17–0.05 Ma), with small-scale eruptions mainly confined to valleys [19,39]. The cone-building stage varied among volcanoes: Wangtian’e cone construction occurred at 3.14–2.12 Ma, whereas Tianchi’s cone-building took place at 1.37–0.01 Ma, predominantly erupting intermediate-silica magma. The caldera-forming stage spanned from ca. 0.01 Ma to AD 946, and the Tianchi caldera was ultimately formed by the “Millennium Eruption” in AD 946, an extremely violent event whose products were widely dispersed across the Changbai Mountain area and even to Japan, the Russian Far East, and Greenland [41,42]. Subsequently, Changbai Mountain experienced minor eruptions in 1403, 1668, 1702, and 1903 [19].

2.3. Hydrogeological Characteristics

The Changbai Mountain area is characterized by widely developed faults and abundant meteoric precipitation. A significant amount of precipitation infiltrates underground along faults and mixes with hot water in the geothermal reservoirs, forming a relatively well-established surface water–groundwater circulation system. The formation and distribution of groundwater in the region are governed by sedimentation, magmatic activity, metamorphism, folding, and faulting. Intense volcanic activity can be divided into five eruptive cycles. Multi-stage eruptive volcanic breccia and basalt constitute the primary water-bearing formations; variations in eruptive stages and structural types lead to differing degrees of vesicle and fissure development, resulting in notable heterogeneity in the water abundance of these aquifer groups. Sedimentary limestone from the Ordovician,

Cambrian, and Sinian ages is present in the area and forms the main carbonate fissure-karst water aquifer [20,22,43].

The Changbai Mountain region experiences distinct seasons with abundant summer rainfall and winter snowfall. Controlled by differences in groundwater types, the characteristics of recharge, runoff, and discharge vary distinctively. Clastic rock pore water is primarily recharged by meteoric precipitation and surface water and discharges mainly in the form of springs. Carbonate fissure-karst water is mainly replenished by precipitation infiltration and the leakage of surface water and overlying phreatic water, discharging as springs along piedmont depressions, inter-mountain valleys, and contacts with non-soluble rocks. Basalt vesicular and fissure water also relies on meteoric water as its main recharge source; around the margins of basalt plateaus, it additionally receives lateral runoff recharge from bedrock fissure water in mountainous areas. This groundwater emerges as springs or discharges to river valleys, with a portion lost to evaporation in shallow burial zones. Bedrock fissure water is directly recharged by infiltrating meteoric precipitation, discharges as springs, and accumulates through runoff toward piedmont depressions and inter-mountain valleys, forming swamps and wetlands [43–46].

The high-temperature hot springs around Tianchi (e.g., Julong and Jinjiang) are mainly associated with the mixing of deep carbonate fracture-karst water and deep fluids ascending along fault zones. In contrast, the peripheral low-temperature springs (e.g., Shibadaogou and Xianrenqiao) are predominantly recharged by shallow vesicular basalt water and bedrock fracture water, characterized by shallow circulation depths, short flow paths, and a greater influence of meteoric water.

2.4. Geophysical Characteristics

Variations in deep structure often serve as the fundamental control on upper-crustal geological phenomena; therefore, clarifying the deep thermal background constitutes a crucial “bottom-up” approach to understanding the formation of geothermal resources. The deep structure of the Changbai Mountain area has long been a focus of geophysical research, and multiple survey methods have revealed its subsurface characteristics. Currently, geophysical methods such as magnetotellurics, seismic controlled-source, seismic attenuation, receiver function, and surface wave techniques are widely applied to investigate the crust–mantle structure beneath Northeast China and the Changbai Mountain area [47], providing an important window into deep geodynamic processes.

Seismic tomography images reveal a stagnant Pacific slab within the mantle transition zone beneath Northeast China, with a thickness of approximately 100 km [26,35,48]. The Pacific Plate subducts to the 660 km discontinuity at approximately 130° E longitude, where it becomes horizontally stagnant and extends 800–1000 km westward. A large mantle wedge has developed above the stagnant slab, shaping the typical crust–mantle structural signature of Northeast China [37]. The volcanic magmas in the Changbai Mountain area all originate from the mantle transition zone [48,49]. The specific figure is shown below (Figure 2) [50].

A low-velocity anomaly extending from the surface to the upper mantle has been detected beneath the Changbai Mountain area, providing evidence for mantle upwelling [51]. Receiver function H- κ stacking results show that V_p/V_s ratios range from 1.7 to 1.8 in the periphery of the Changbai volcanic field and progressively increase to 1.87–1.93 toward Tianchi Volcano, indicating the presence of a partial melt body within the crust [36,47]. Vertically, a shallow magma chamber may exist at depths of 5–10 km in the crust [36]. A dipping low-velocity layer is observed within the crust, being shallowest beneath the volcano and deepening with increasing distance from the edifice; grid-search inversions reveal a marked reduction in S-wave velocity at depths of 4–8 km, and common conversion point migration

images show that the low-velocity anomaly extends laterally from the shallow subsurface to approximately 30 km [47]. A trans-dimensional Bayesian joint inversion of teleseismic receiver functions and ambient-noise Rayleigh wave group velocity dispersion indicates a low-velocity zone at middle crustal depths of 8–15 km, stretching roughly 100 km in a north–south direction, which may represent a magma chamber; low-velocity anomalies in the upper mantle are also present and are likely associated with the upwelling of hot and wet asthenospheric material triggered by Pacific Plate subduction [16]. Ambient noise and surface wave tomography reveal low- V_s anomalies within the crust and upper mantle beneath Changbai Mountain; a pipe-like low- V_s zone in the upper crust is interpreted as a magmatic conduit, whereas the magma chamber in the middle–lower crust is attributed to decompression melting of upwelling asthenospheric material from the mantle transition zone [52]. Magnetotelluric data identify three high-conductivity anomalies at depths of 3–5 km, 10–16 km, and 40–60 km, interpreted as a porous brine layer, a magma chamber with 7–30% melt fraction, and decompression melting caused by asthenospheric upwelling, respectively [53]. Three-dimensional crustal S- and P-wave velocity models suggest the existence of a high V_p/V_s zone at approximately 5 km depth beneath Tianchi Volcano, inferred to be a magma chamber; another magma chamber may reside at around 15 km depth in the middle crust, feeding the shallower chamber [17]. To provide a detailed description of the magma chamber system in the Changbaishan area, this study divides the system into shallow magma chambers (hosted in the crust) and deep magma chambers (hosted in the mantle). The details are presented below (Table 1).

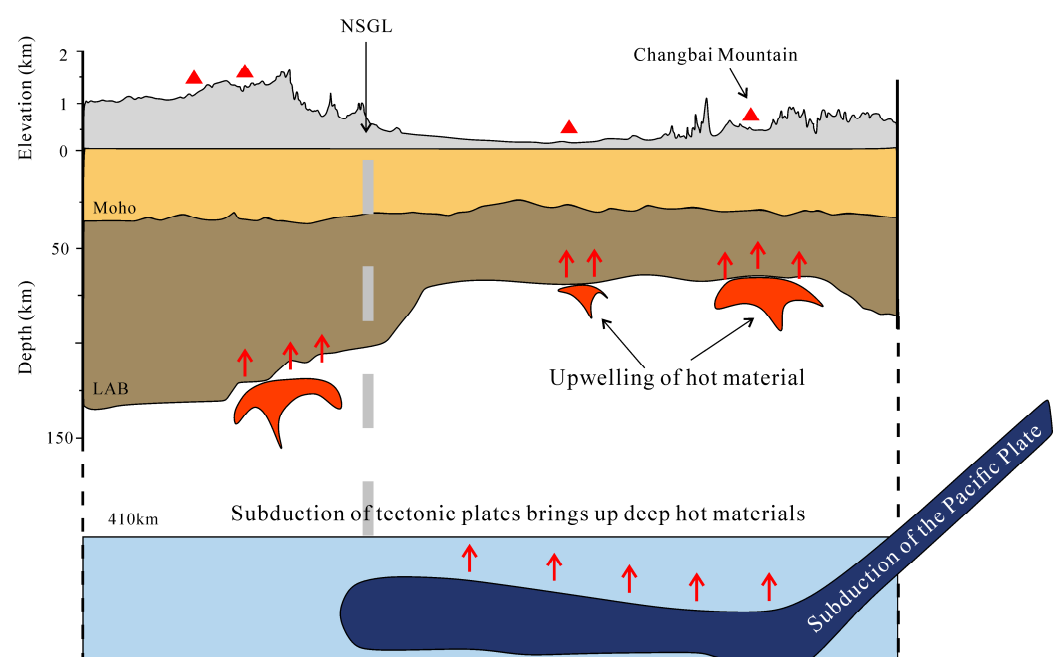


Figure 2. Schematic diagram of the deep structure in eastern China [50].

Table 1. Summary of interpreted magma chamber depths beneath the Changbai Mountain area.

Magma Chamber	Depth	Method	References
Shallow magma chamber	9 to 15 km	Artificial seismic	[54]
	>10 km	Seismic tomography results	[17]
	8 to 14 km	Numerical Simulation	[8]
Deep magma chamber	38 to 65 km	Seismic tomography results	[16]
	30 to 60 km	Magnetotelluric inversion	[15]

In summary, multiple geophysical surveys consistently indicate the presence of partially molten magma chambers within the crust beneath the Changbai Mountain area. These chambers are closely linked to asthenospheric upwelling, and the shallow magma chamber is still subject to sustained replenishment at present [5,18]. Although a consensus has not yet been reached on the precise emplacement depths and spatial extent of these magma chambers, it is generally accepted that two chambers exist: one in the upper crust and another in the middle–lower crust [36]. Compared with other parts of Northeast China, the magma chambers in the Changbai Mountain area exhibit a significantly higher melt fraction and shallower burial depths; their heat dissipation is expected to substantially elevate the regional geothermal temperature field.

2.5. Materials and Methods

To elucidate the aggregation of high-temperature geothermal resources in the Changbai Mountain area, this study quantitatively estimates crustal radiogenic heat production and residual deep/mantle heat flow along a representative 2D profile. The possible contribution of crustal partial melt bodies is discussed separately based on previous numerical simulations and geophysical evidence. It then examines key controls on the present-day geothermal field, focusing on stratigraphic heat conduction, subsurface fluid migration, and fault systems. Finally, by integrating the distribution of these resources, Meso-Cenozoic tectono-thermal evolution, deep geodynamic processes, and essential geothermal system elements (heat source, water source, reservoir, pathway, caprock), a bottom-up genetic mechanism for the typical high-temperature geothermal resources is established.

Heat source is a fundamental component of geothermal systems and controls the thermal regime of reservoirs. Numerically, the heat source is characterized by the conductive terrestrial heat flow, which can generally be partitioned into three components: conductive heat flow from the mantle, radiogenic heat production in the crust, and heat dissipation from possible partial melt bodies within the crust, as expressed in Equation (1):

$$q = q_m + q_p + q_c = q_m + q_p + \sum (D_i \times A_i) \quad (1)$$

where q is the surface conductive heat flow (mW/m^2); q_m is the mantle conductive heat flow (mW/m^2); q_p is the heat dissipation from possible partial melt bodies within the crust (mW/m^2); q_c is the radiogenic heat production in the crust (mW/m^2) and $q_c = \sum (D_i \times A_i)$; D_i is the thickness of the i -th crustal layer (km); and A_i is the heat production rate of the i -th layer ($\mu\text{W}/\text{m}^3$). Crustal radiogenic heat production can be further partitioned into contributions from sedimentary layers, basement, middle crust, and lower crust.

The calculation principle of this formula is as follows: based on the thickness and radiogenic heat production rate of each layer, the radiogenic heat production of each individual layer is computed. The crustal heat flow is then taken as the sum of the radiogenic heat production of all layers. In the present profile, no magma chamber is identified and the heat-flow partitioning is simplified to ($q = q_m + q_c$). Therefore, the residual ($q - q_c$) is reported as mantle/deep heat flow for this profile. The magma-chamber contribution is discussed separately using previous numerical simulations and evidence.

3. Geothermal Factors of the High-Temperature Geothermal System

3.1. Heat Source

To clarify the heat source structure in the Changbai Mountain area, a refined crustal model is required. However, a sufficiently detailed three-dimensional crustal structure is currently lacking in this region. To clearly elucidate the spatial distribution of the heat

source structure, this study adopts a two-dimensional crustal structural profile previously interpreted from magnetotelluric sounding (Figure 3b) for analysis. Since no magma chamber system is identified in this profile and Equation (1) is not applicable to the three-component scenario involving simultaneous consideration of crustal heat flow, mantle heat flow, and magma chamber heat flow, this study quantitatively calculates only the crustal and mantle heat flow. The crustal heat flow is calculated by summing the radiogenic heat production from the individual rock layers, and the mantle heat flow is obtained by subtracting the crustal heat flow from the surface heat flow. The surface heat flow values along the profile are taken from the Changbai Mountain area estimates derived from Curie depth and temperature. Based on the actual longitude and latitude coordinates of the selected typical profiles, this study obtained the required surface heat flow values from previous works. These values range from 81.8 to 83.2 mW/m², with an average surface heat flow along the profile of approximately 82.5 mW/m² (Table 2) [11,55].

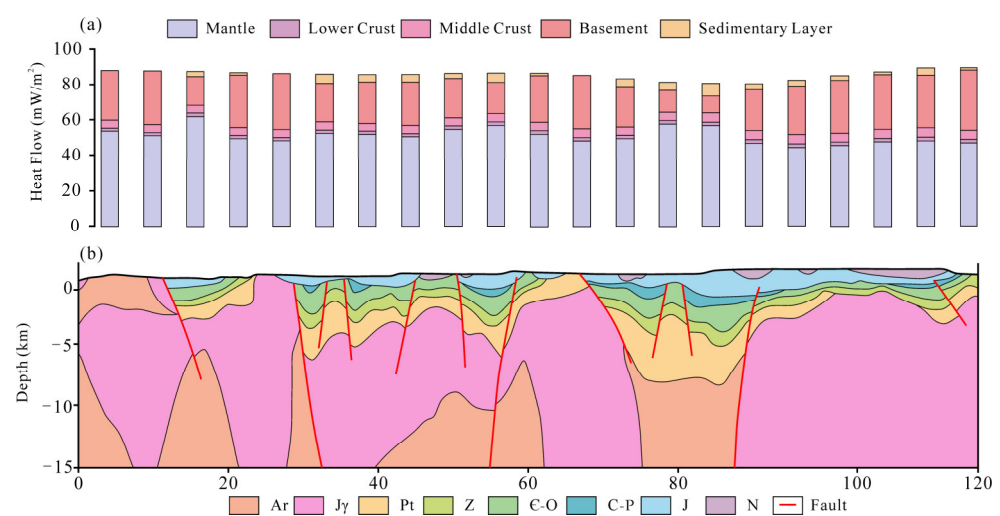


Figure 3. (a) Two-dimensional cross-sectional heat source structure of the Changbai Mountain area; (b) Two-dimensional geological cross-section of the Changbai Mountain area obtained by the magnetotelluric method [6].

In Figure 3, Q denotes Quaternary strata, N denotes Neogene strata, K denotes Cretaceous strata, J denotes Jurassic strata, T denotes Triassic strata, P denotes Permian strata, C denotes Carboniferous strata, O denotes Ordovician strata, € denotes Cambrian strata, and Z denotes Sinian strata. These stratigraphic symbols, when appearing subsequently in the text, carry the same meanings.

The detailed two-dimensional geological cross-section of the area enables a refined calculation of the heat source structure. To precisely calculate the heat source structure of the Changbai Mountain area, this study, based on the stratigraphic characteristics of the region, decomposes the crustal heat flow into four components: heat contribution from the sedimentary layer, basement, middle crust, and lower crust. The average rock heat production rates used for each stratigraphic unit are summarized in Table 3. The radiogenic heat production rates from the Quaternary to the basement were obtained from previous measurements by our research group and from published values for corresponding strata in surrounding areas.

Table 2. Two-dimensional profile coordinates of data points and surface heat flow retrieval.

Point	Profile Coordinates	Read Surface Heat Flow (mW/m ²)
1	(0, 0)	82.6
2	(0, 6)	82.5
3	(0, 12)	82.6
4	(0, 18)	82.6
5	(0, 24)	82.5
6	(0, 30)	82.3
7	(0, 36)	82.4
8	(0, 42)	82.6
9	(0, 48)	82.7
10	(0, 54)	82.9
11	(0, 60)	83.2
12	(0, 66)	82.7
13	(0, 72)	82.2
14	(0, 78)	82.0
15	(0, 84)	81.8
16	(0, 90)	81.9
17	(0, 96)	82.1
18	(0, 102)	82.3
19	(0, 108)	82.5
20	(0, 114)	82.8
21	(0, 120)	83.2

Table 3. Heat production rates of stratigraphic and crustal units used in the heat-flow calculation [10,56–60].

Stratum	Heat Production Range (μW/m ³)	Average Heat Production (μW/m ³)
Q	0.42–3.24	1.65
N	0.27–0.98	0.63
K	0.82–2.52	1.86
J	0.31–1.91	1.09
T	1.90–2.18	2.04
P	0.78–2.57	1.42
C	2.03–3.18	2.57
O	0.11–0.25	0.18
Є	0.32–2.91	1.98
Z	0.57–1.19	0.88
Basement	0.54–2.81	1.43
Middle Crust	0.46	0.46
Lower Crust	0.22	0.22

(Only a single reference value is available for the heat production rates of the middle and lower crust, with no range data.)

To calculate the heat source structure of each part of the two-dimensional profile in detail, we first digitized the stratigraphic boundaries, selected several calculation points on the surface of the profile, and extended these points vertically downward to obtain a number of one-dimensional profiles. Based on the digitized two-dimensional profile, the thickness of each stratum was determined. Subsequently, the heat production of each stratum and the crustal heat flow for the individual one-dimensional profiles were calculated from the stratum thicknesses and the corresponding radiogenic heat production rates.

The calculation results show that, due to localized absence and generally limited thickness, the heat production from sedimentary layers ranges from 0 to 6.8 mW/m², with an average of 2.7 mW/m², accounting for 0–8.2% (average ~3.3%) of the surface heat flow (Figure 3b). The thin sedimentary cover thus contributes little radiogenic heat. Basement heat production ranges from 9.8 to 29.3 mW/m², averaging 22.4 mW/m², and represents the dominant component of crustal heat flow, accounting for 11.9–35.5% (average ~27.2%) of the surface heat flow. The middle crust produces 4.6–5.3 mW/m² (average 4.9 mW/m²), and the lower crust produces 1.7–2.0 mW/m² (average 1.8 mW/m²), both making relatively minor contributions. Finally, integrating all crustal layers, the crustal heat flow along the profile in the Changbaishan area ranges from 23.5 to 38.6 mW/m², with an average of 32.9 mW/m², accounting for 28.5–46.8% of the surface heat flow (approximately 40%). The mantle heat flow ranges from 43.9 to 58.9 mW/m², with an average of 49.6 mW/m², accounting for 53.2–71.5% of the surface heat flow (approximately 60%). These results indicate that the Changbaishan area represents a ‘cold crust–hot mantle’ geothermal system, which is consistent with previous understandings [61].

Regarding the heat production of the magma chamber system, previous studies have performed numerical simulations and quantitative analyses of the present-day geothermal field in the Changbaishan area based on the three-dimensional heat conduction equation. Their results show that the surface heat flow in the Tianchi volcanic area can reach up to 130.8 mW/m², with the magma chamber system contributing approximately 53.1 mW/m² as a heat source [10]. This heat source contribution from the magma chamber system is higher than the maximum crustal heat flow calculated in this study and is comparable to the maximum mantle heat flow. However, the heat flow contribution of the magma chamber system to the region is not only manifested as a conductive heat supply through high-temperature baking, but also as a convective heat supply to the geothermal reservoir fluids, because the upwelling of deep materials undergoes decompression and cooling, continuously releasing high-temperature volatile components that mix into the reservoir fluids along fracture pathways [5]. If the conductive and convective heat supplies from the magma chamber system are considered together, their contribution to the regional heat source will exceed the standalone crustal and mantle heat flows. This is also reflected to a certain extent in the measured terrestrial heat flow data from boreholes. Previous studies have calculated terrestrial heat flow for four geothermal wells in the Changbaishan area based on borehole data. Among them, the measured heat flow of the geothermal well located in the Tianchi volcanic area within the influence zone of the magma chamber system reaches 270 ± 16 mW/m², whereas the measured heat flow of geothermal wells located at the margin of the Changbaishan area, outside the influence zone of the magma chamber system, ranges from 75 to 82 mW/m² [8]. This large difference strongly supports a major local thermal influence of the magma chamber system in the Tianchi volcanic area. Therefore, this study concludes that the primary heat source in the Changbaishan area is the multi-level heat supply from the magma chamber system through both conductive and convective processes, followed by mantle heat supply, and finally crustal heat supply derived from the radiogenic heat production of rocks.

3.2. Cap Rock and Geothermal Reservoir

The Changbai Mountain volcanic field experienced large-scale eruptions during the Cenozoic, during which voluminous mantle-derived basalts were extruded and covered the entire area. Extrusive rocks formed by volcanic effusion are generally characterized by low porosity, low permeability, and low thermal conductivity [62], and the basaltic layers in the Changbai Mountain area share these properties. Based on previous test data, the permeability of the basalt layers in the Changbaishan area is approximately 7.5×10^{-16} m²,

and the porosity is about 1% [9], indicating that both the porosity and permeability of most basalt layers in the area are at relatively low levels. The thick basaltic cap covering the surface acts as an excellent caprock for the high-temperature volcano-geothermal system, effectively reducing subsurface heat loss. Furthermore, although a certain fracture network is developed within the basalts, their permeability remains significantly lower than that of the underlying sedimentary layers and basement [9], and is sufficient to form an effective fluid seal over the underlying strata. Although some basalt layers in the Changbaishan area exhibit relatively high permeability and porosity, such layers are, on the whole, in the minority and have little influence on the sealing effect of the thick basalt sequence against subsurface fluid flow and heat transfer. Therefore, this study concludes that the thick basaltic layer blanketing the surface of the Changbai Mountain area constitutes a regional preferable caprock.

A geothermal reservoir requires strata with sufficient temperature; hydrothermal reservoirs additionally demand high porosity and permeability, whereas hot dry rock reservoirs do not. In the Changbaishan area, the clastic rock layers have porosities ranging from approximately 1.6% to 7.2% and a permeability of about $3.4 \times 10^{-13} \text{ m}^2$; the carbonate rocks have a porosity of about 4.5% and a permeability of about $1.0 \times 10^{-12} \text{ m}^2$ [9]. Although these porosities are relatively low compared to those of sedimentary basin geothermal systems, they are already relatively high for the volcanic geothermal system of the Changbaishan area. Meanwhile, the permeabilities of both the clastic and carbonate rock layers in this area are at relatively high levels. Therefore, this study considers the clastic and carbonate rock layers to be the hydrothermal reservoirs in the Changbaishan area. A geothermal reservoir requires not only favorable physical properties of the rock formations but also high temperature characteristics. Carbonate rocks are primarily distributed in the Sinian, Cambrian, and Ordovician systems, while clastic rocks are widespread within the sedimentary sequence [12,20,43]. Shallow strata lack adequate temperature and are thus unsuitable as geothermal reservoirs. Therefore, this study considers that the relatively deep carbonate and clastic rock layers hosted in the Sinian, Cambrian, and Ordovician strata serve as hydrothermal reservoirs in the Changbaishan area (at depths of 2–4 km, with temperatures of approximately 150–200 °C), whereas the deeper basement constitutes potential hot dry rock (HDR) reservoirs (at depths > 5 km, exceeding 200 °C). The temperature estimates for the hydrothermal reservoirs are based on previous geochemical geothermometers and numerical simulation results, while those for the potential hot dry rock (HDR) reservoirs are based on previous numerical simulation results and the extrapolation of borehole temperature profiles in the Changbaishan area.

Although the hydrothermal reservoirs in the Changbai Mountain area possess promising resource potential, existing hot spring data and borehole depths are insufficient to directly reveal the deep reservoir temperatures. To address this, previous studies have employed geochemical geothermometers, estimating reservoir temperature, depth, and circulation depth through hydrochemical analyses of water samples from hot springs and geothermal wells, thereby further quantifying the characteristics of hydrothermal reservoirs. The geothermometers used include quartz, chalcedony, Na-K, Na-K-Ca, K-Mg, CO_2/H_2 , and H_2/Ar , with results summarized in Table 4. As shown, the average estimated reservoir temperatures for the Julong and Jinjiang hot spring groups range from 150 to 200 °C, indicating favorable high-temperature geothermal resource characteristics, whereas the Shibadaogou and Xianrenqiao hot spring groups exhibit relatively lower temperatures, typical of medium-to-low temperature geothermal resources. Among the four spring groups, the Julong and Jinjiang groups are located adjacent to the Tianchi Volcano, while the Shibadaogou and Xianrenqiao groups lie on the margin of the Changbai Mountain area. Therefore, this study attributes the temperature difference between the two sets of hot

springs primarily to the influence of the magma chamber system centered beneath the area. Furthermore, discrepancies exist among different geothermometer results: most geothermometers yield relatively consistent estimates, but the K-Mg geothermometer yields values lower than the majority, likely due to cold-water mixing that severely disturbs its response to reservoir temperature [6]. In contrast, gas geothermometers represented by CO₂/H₂ yield significantly higher temperature estimates than silica and cation geothermometers, suggesting that the reservoir temperature in the Changbai Mountain area may be related to deep-seated gases and indicating additional heat input from deeper sources.

Table 4. Estimated temperatures of geothermal reservoirs in the Changbai Mountain area based on geochemical thermometers of hot springs [6,39,43,61–66].

Water Sample	Geochemical Geothermometer (°C)						
	Quartz	Chalcedony	Na-K	Na-K-Ca	K-Mg	CO ₂ /H ₂	H ₂ /Ar
Julong Hot Spring Group	155–194.3	135.4–162.7	189.5–189.8	157	94	251.2	245
Jinjiang Hot Spring Group	147.5–180.5	124.4–160.2	208.7–217.3	172.5	77.5	234.5	129.7
Shibadaogou Hot Spring Group	103.5–130.3	73.8–102.3	157.6–158	137.3	68.3	246.1	Not available
Xianrenqiao Hot Spring Group	117.6–136	89–109	152	132	66	Not available	Not available

3.3. Water Source and Pathway

The water source of the geothermal system in the Changbai Mountain area is primarily derived from meteoric water and snowmelt. The groundwater storage spaces are diverse: bedrock and carbonate rocks feature well-developed fissures and can be directly exposed at the surface, receiving recharge from meteoric water and surface water; basaltic and clastic rocks, dominated by pores, vesicles, and fissures, are mainly recharged by meteoric infiltration, lateral bedrock inflow, and surface water [43,46]. Hydrochemical analyses of the hot springs reveal evidence of evaporation, indicating mixing with surface water during deep fluid migration [22,43]. The low ion concentrations suggest short circulation times and strong mixing with cold surface water [20,23]. Gas geochemical isotopes indicate a mantle-derived signature for the hot springs, and boron contents suggest admixed magmatic gas, closely related to the magma chamber formed by mantle upwelling [5,23]. The above evidence collectively demonstrates that the geothermal fluids in the Changbai Mountain area are recharged not only by meteoric water and snowmelt but are also connected with volatile components exsolved from the magma chamber, receiving additional heat input from depth.

Fault systems serve as efficient fluid migration pathways in geothermal systems, capable of hydraulically connecting fluid systems across different strata. Faults are highly developed in the Changbai Mountain area. The widely developed faults likely provide potential pathways for recharge and upflow, but the hydraulic roles of individual faults remain poorly constrained and require further numerical or field-based investigation. Meanwhile, these well-developed faults also enhance the recharge intensity of meteoric water and surface water, causing mixing between infiltrating water and deep hot water, thereby reducing the temperatures of hot springs and reservoirs.

4. Discussion

4.1. Framework for Model Construction

The aggregation model and genetic mechanism presented in this study are not derived from a single numerical simulation or inversion, but rather synthesized from multiple independent lines of evidence following a “bottom-up” integration workflow. The construction of the model proceeds in three stages:

First, individual geothermal system elements (heat source, caprock, reservoir, pathway, and water source) are characterized separately in Section 3 based on distinct datasets: heat source structure from heat-flow decomposition (Section 3.1); caprock and reservoir lithology from stratigraphic and petrophysical analysis (Section 3.2); water source and pathways from hydrogeochemical and structural data (Section 3.3). Each element is constrained by its own independent data type, reducing the risk of circular reasoning.

Second, the spatial and genetic relationships among these elements are examined by cross-correlating their distributions. For example, the spatial coincidence of high reservoir temperatures (from geothermometry) with the inferred magma chamber location (from geophysics) and the clustering of hot springs along major faults (from structural mapping) provides the basis for interpreting fault-controlled heat transport from the magma chamber to the shallow reservoirs.

Third, the individual element characterizations and their spatial correlations are integrated into a coherent conceptual model (Figure 4) that explains how mantle upwelling, crustal magma chambers, fault systems, basaltic caprock, and meteoric recharge work together to produce the observed geothermal anomaly pattern. This model is interpretative rather than predictive; it does not replace a fully coupled numerical simulation but serves as a testable hypothesis for future quantitative modeling and exploration drilling.

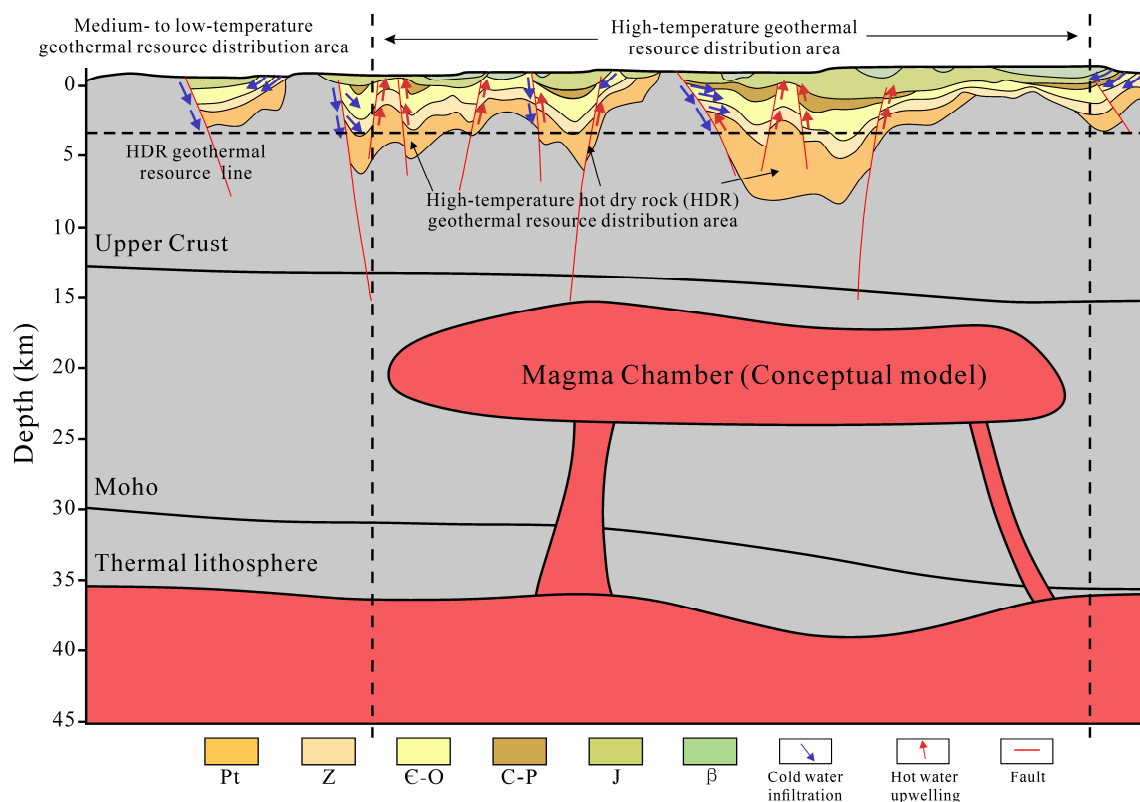


Figure 4. Aggregation model and genetic mechanism of hydrothermal geothermal resources and hot dry rock (HDR) geothermal resources in the Changbai Mountain area.

The strength of this approach lies in its convergence of multiple independent datasets, while its main limitation is the lack of direct deep borehole calibration. Therefore, a sensitivity analysis of the key parameters applied in this study was conducted in a later section (Section 4.3) to verify the stability and reliability of the resulting model.

4.2. Genetic Mechanism of the High-Temperature Geothermal System in the Changbai Mountain Area

Based on the preceding analysis of geothermal system elements, the formation and aggregation processes of geothermal resources in the Changbai Mountain area are further examined. By integrating the present-day geothermal temperature field, the distribution characteristics of high-temperature geothermal resources, the tectono-thermal evolution history, deep geodynamic processes, the effective heat source architecture, and the key factors governing modern geothermal aggregation, an aggregation model and genetic mechanism for the typical high-temperature geothermal system in this region are established (Figure 4).

The Changbai Mountain area hosts various geothermal resources, including hydrothermal and hot dry rock (HDR) types. Hydrothermal resources are further divided into medium–low temperature and high-temperature categories. Given the well-developed faults in the region, hot springs represent the most direct manifestation of hydrothermal geothermal resources. Numerous hot springs occur in the Changbai Mountain area, with those in peripheral zones exhibiting lower temperatures and those within the volcanic field showing higher temperatures [22,43]. This study attributes this disparity to the non-uniform thermal influence of the magma chamber system: reservoirs beneath the volcanic field, being closer to the magma chamber, are continuously heated and thus attain higher temperatures than those in the periphery, demonstrating favorable high-temperature geothermal potential. Previous numerical simulations of the central temperature field have revealed that temperatures can exceed 150 °C at depths of 3–5 km [8,9]. Accordingly, this study concludes that the Changbai volcanic area hosts high-temperature hydrothermal resources, whereas the peripheral areas predominantly contain medium–low temperature hydrothermal resources. Furthermore, the underlying Proterozoic strata consist primarily of dense, low-porosity, and low-permeability metamorphic rocks, whose impermeable nature effectively prevents temperature reduction from cold-water infiltration. As the Proterozoic strata beneath the volcanic area are closer to the magma chamber than the hydrothermal reservoirs, they receive more heating. Hence, this study proposes that these Proterozoic strata constitute an potential HDR formation with considerable geothermal power generation potential.

The genetic mechanism of the geothermal system in the Changbai Mountain area is complex but is predominantly controlled by its tectonic setting. Situated in Northeast China and influenced by the subduction of the Pacific Plate, the region has experienced mantle upwelling and thermal lithospheric thinning, which have elevated the mantle heat flow background. Crustal radiogenic heat production provides a stable heat contribution, while the magma chamber system within the crust continuously heats the surrounding rock and steadily supplies additional heat through conduction. Meanwhile, geochemical evidence of mixing between reservoir fluids and deep gases indicates hydraulic communication between the reservoirs and deep high-temperature materials [5,6,20]. High-temperature volatile components originating from depth may migrate upward through deep-seated faults into the geothermal reservoir, potentially contributing additional deep heat to the reservoir. Consequently, the enhanced mantle heat flow, crustal radiogenic heat, sustained heating from the magma chamber, and heat supplied by deep volatile components jointly constitute a multi-source heat supply in the Changbai Mountain area. This multi-level, high-quality heat source supports the occurrence of high-temperature geothermal resources, while the thick basaltic caprock effectively minimizes heat loss, and sustained meteoric water recharge together with the extensive fault systems serve as carriers and conduits for heat transport. These elements collectively shape a well-developed high-temperature geothermal system in the Changbai Mountain area, indicating substantial exploration potential for high-temperature geothermal resources.

4.3. Sensitivity Analysis

The genetic model described above integrates multi-source data, including heat flow estimates derived from Curie depth inversion, geochemical geothermometers, and geophysical interpretations of crustal structure, each type of data carrying inherent uncertainties. Therefore, this section discusses the impacts of these data uncertainties on the present study. The $\pm 10\%$ variation in parameters adopted in this section constitutes a scenario-based sensitivity test, rather than a rigorous quantitative uncertainty analysis. This magnitude was chosen based on the typical range of variation in regional rock thermal properties and formation thicknesses, and is intended to test the robustness of the core conclusions—in particular, the “cold crust–hot mantle” thermal structure—to fluctuations in key parameters.

First, the influence of the Curie surface characteristics on the heat flow estimates based on them are considered in this study. The estimation of heat flow from Curie surface characteristics depends on the adopted Curie temperature and depth, but fundamentally, it depends on the variation in geothermal gradient caused by changes in Curie temperature and depth. Terrestrial heat flow is calculated as the product of rock thermal conductivity and the geothermal gradient, being directly proportional to both (Equation (2)). Hence, to evaluate the impact of surface heat flow estimates—subject to uncertainties in Curie depth and temperature—on the conclusions of this study, a sensitivity analysis of the geothermal gradient arising from variations in Curie depth and temperature is conducted. When the regional geothermal gradient increases or decreases by 10%, the surface heat flow changes correspondingly by 10% because the surface heat flow is proportional to the geothermal gradient under the premise that the average thermal conductivity remains constant. Specifically, it would rise or fall by 8.25 mW/m^2 from the average value of 82.5 mW/m^2 . In these two scenarios, the average crustal heat flow of 32.9 mW/m^2 accounts for approximately 44.3% and 36.3% of the surface heat flow, respectively, both below 50%. This still indicates the ‘cold crust–hot mantle’ thermal structure characteristic of the Changbaishan area. Consequently, this study considers that the surface heat flow errors arising from the estimation based on Curie surface characteristics have a minor influence on the conclusions of this study.

$$q = -K \times dT/dZ \quad (2)$$

where q is surface heat flow (mW/m^2); dT/dZ is the geothermal gradient ($^{\circ}\text{C/km}$); K is the rock conductivity ($\text{W/(m} \times \text{K)}$). Multiplying the geothermal gradient in $^{\circ}\text{C/km}$ by the thermal conductivity in $\text{W/(m} \times \text{K)}$ yields $(^{\circ}\text{C} \cdot \text{W})/(\text{km} \cdot \text{m} \cdot \text{K})$. Since the Celsius temperature interval is equivalent to Kelvin and there is no dimensional discrepancy, the temperature units cancel out, giving $(^{\circ}\text{C} \cdot \text{W})/(\text{km} \cdot \text{m} \cdot \text{K}) = \text{W}/(\text{km} \cdot \text{m}) = (1000 \text{ mW})/(1000 \text{ m} \cdot \text{m}) = \text{mW/m}^2$.

With regard to formation thickness and radiogenic heat production rate, since crustal heat flow is essentially the sum of the products of the thickness and heat production rate of each layer (the q_c term in Equation (1)), fluctuations in these two parameters intrinsically have the same effect on crustal heat flow. Therefore, this study uses the impact of variations in heat production rate on the results and the thermal structure conclusions to represent the combined impact of uncertainties in both heat production rate and formation thickness. By uniformly increasing and decreasing the radiogenic heat production rate of each layer by 10%, the crustal heat flow, according to the q_c term in Equation (1), will also proportionally increase and decrease by 10%. Specifically, the average crustal heat flow would fluctuate from 32.9 mW/m^2 to approximately 36.2 mW/m^2 and 29.6 mW/m^2 , and the proportion of crustal heat flow to surface heat flow would vary to about 43.0% and 35.9%, respectively, both remaining below 50%. This still indicates the ‘cold crust–hot mantle’ thermal structure characteristic of the Changbaishan area. Hence, this study considers that the errors in

crustal heat flow arising from uncertainties in heat production rate and formation thickness have a minor influence on the conclusions of this study.

As for reservoir temperatures estimated by geochemical geothermometers, the values obtained for the Changbaishan area are relatively scattered (Table 4). However, because the Changbaishan area is a volcanic geothermal system, the predictions from silica and cation geothermometers often suffer from errors caused by cold-water mixing and the influx of exotic gases in such systems. In contrast, the gas geothermometer data in Table 4, which are the most suitable for this type of geothermal system, show good stability, and all estimated reservoir temperatures above 200 °C indicate high reservoir temperatures in the area. Gas geothermometers provide useful constraints on deep thermal conditions and volatile input in this volcanic geothermal system, but they may not directly represent shallow hydrothermal reservoir temperatures. Nevertheless, the gas geothermometers clearly reveal the high-temperature geothermal characteristics of the area. It can thus be seen that, although discrepancies exist among the estimates from different geochemical geothermometers, these discrepancies do not affect the conclusion that the Changbaishan area is classified as a high-temperature geothermal system. Multiple lines of evidence, including borehole heat flow, numerical modeling, hot-spring temperatures, and selected geothermometers, support high-temperature potential.

5. Conclusions

- (1) The heat-flow calculation indicates that crustal radiogenic heat contributes approximately 40% of the surface heat flow along the selected profile, implying a dominant residual deep heat contribution. In combination with previous numerical simulations and borehole heat-flow data from Tianchi, the magma chamber system is inferred to be a major local heat source in the volcanic center.
- (2) The available evidence suggests that the Changbai Mountain area contains the main elements of a geothermal system, including deep heat sources, fault-related pathways, meteoric recharge, potential hydrothermal reservoirs, possible HDR targets, and locally sealing basaltic units. These elements are spatially coupled and jointly control the distribution of geothermal anomalies.
- (3) The formation of the high-temperature geothermal system is ultimately controlled by deep dynamic processes associated with the subduction of the western Pacific plate, which have induced mantle upwelling, lithospheric thinning, and the establishment of a crustal magma chamber system. Under the combined effects of multi-source heat supply, fault-controlled fluid circulation, and cap rock sealing, a high-temperature anomaly zone centered on Tianchi volcano has been formed, indicating that the deep hot dry rock reservoirs possess considerable potential for both hydrothermal power generation and potential HDR development.

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