Research Article

Hydrogeochemical Characteristics and Genesis Model of Jinjiang and Julong Hot Springs in Changbai Mountain, Northeast China

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Changbai Mountain in China has been explored as a potential area for its rich hot springs including the Jinjiang and Julong hot spring groups. The hydrogeochemical characteristics and conceptual genesis models of the Jinjiang and Julong hot springs were evaluated by hydrogeochemical analysis, isotope analysis, rock sample analysis, hydrogeochemistry simulation, and geophysical exploration method. The results showed that HCO_3^- and Na^+ were the most abundant anion and cation in the hot springs, and the hydrochemical type was Na-HCO_3 . And the hot springs are enriched with trace components such as H_2SiO_3 and Sr. The major gas composition of the Jinjiang hot springs and Julong hot springs were CO_2 , N_2 , and CH_4 , which were derived from the mantle. The chemical compositions were produced by feldspar and pyroxene mineral hydrolysis. The recharge source of the hot springs was atmospheric precipitation and was also influenced by evaporation, and the genetic models for the Jinjiang hot springs and Julong hot springs were as follows: the heat source of both was a magma body and heat was mainly migrated in the form of thermal conduction. The cap rocks were both composed of trachyte of Baitoushan formation, basalt of Junjianshan formation, and rhyolitic pyroclastic rocks of Changbai formation. The geothermal reservoir of both hot springs was a fracture zone with the lithology of volcanic breccia, sand, and gravel and volcanic breccia and marble, respectively.

1. Introduction

Geothermal resources are being researched and developed as renewable and clean energy all over the world because of its rich reservoir, renewable resources, reliability, and environmental acceptability [1]. Hydrogeochemical composition is an important indicator for the quality evaluation of geothermal resources that reflects the formation evolution process, interaction between geothermal fluid and rock, and geothermal fluid circulation condition [2]. The hydrogeochemical compositions also have the vital role for corrosion and scaling, geothermal reservoir temperature evaluation, and geothermal fluid uses. In recent decades,

many countries have conducted much research in geothermal water resource exploitation.

Changbai Mountain is located in the east of the Songliao Basin, China, and is a tectonically and volcanically active area. Due to the previous volcanic activities, the region is rich in geothermal springs, which are discharged at different altitudes. The monitoring of geothermal fluid of Changbai Mountain began in 1985, and the main monitoring compositions include CO_2 , N_2 , He, H_2 , O_2 , and CH_4 which were associated with volcanic activities [3]. Tianchi volcano is one of the famous active volcanoes in China. Its eruptive history included early shield-forming, middle cone construction, and late ignimbrite-forming eruptions in three stages [4].

The eruptive products were alkali and tholeiitic basalts, trachyte and comendite lavas, and pyroclastic equivalents [5]. So what are the hydrogeochemical characteristics of the hot springs and what are the sources of the hydrogeochemical compositions on the complex geothermal geological environments? Solving these problems are vital for the development and utilization of geothermal water resources.

The heat source, heat reservoir, heat conduction channel, and cap rock are four basic elements for the geothermal water system [6]. Study of the geothermal water system model is an important means to reveal the formation and distribution of a geothermal field. At present, the geothermal water system model mainly includes a simple conceptual model, analytical model, lumped parameter model, and distributed parameter model [7]. The geothermal field characteristics of the New Zealand Wairakei-Tauhara were revealed by a simple concept model. The hot water welled up to the surface through the NE-SW fracture, and the heat reservoir temperature ranged from 260 to 300°C [8]. Based on two-dimensional groundwater flow theory, the heat conduction model of Leibnitzer geothermal field was established by using FEFLOW software [9]. The heat sources of the Obama geothermal water system in Japan were studied by three-dimensional numerical model [10].

Geothermal exploration is the most direct method to probe and identify geothermal resources, which can be used to deeply and fully understand the geothermal resource forming process [11]. Geophysical exploration for the subsurface geothermal reservoir began in early 1980 which was a geothermal exploration, mainly employing shallow electrical resistivity surveys [12]. Nowadays, the common geophysical exploration methods are the geoelectrical method, thermal method, seismic method, magnetic measurement method, and gravimetric method [13]. Newman et al. [14] expounded the characteristics of the Coso geothermal field and the relationship with tectonic fissures by using 3D magnetotelluric exploration method.

At present, the developed geothermal springs of Changbai Mountain were utilized for balneology and spa purposes. Most of the geothermal spring resources are still not developed. Among the hot springs, the Julong springs and Jinjiang springs have the highest flow quantity and temperature in this region. The distribution areas and flow quantity of the Julong springs and Jinjiang springs are, respectively, 3317.50 m² and 210.0 m² and 6455.48 m³/d and 578.8 m³/d. Nowadays, the local government has enhanced the development of the geothermal springs, and some geothermal water diversion projects were established. But the hydrogeochemical characteristics, recharge sources, and genesis model of the Julong springs and Jinjiang springs are not clear. Therefore, in order to develop, use, and protect the geothermal springs, studying the hydrogeochemical characteristics, recharge sources, and genesis model of geothermal springs is urgently needed. In this study, the Julong springs and Jinjiang springs were comprehensively analyzed via sampling and monitoring of geothermal spring water for hydrogeochemical characteristics and genesis model, isotope analysis, and geophysical exploration. The results of the research would promote the development and utilization of geothermal resources and enrich the genesis mechanism of the geothermal system.

2. Study Area and Volcano Geology

Julong springs and Jinjiang springs are located in the Changbai Mountain basalt area in the east of Jilin Province. Geographical coordinates are located in the north latitude of 41°23′–42°35′ and east longitude of 127°15′–129°00′. The area has a temperate continental monsoon climate with an annual average temperature of 3.5°C. According to Changbai Mountain weather stations, the annual average precipitation is 1332.6 mm, much of which occurs during the period from June to September.

The geological groups in the Julong spring and Jinjiang spring areas mainly include Proterozoic Laoling formation (Pt_{1z}), Triassic Changbai formation (T_{3c}), Cenozoic Pleistocene Junjianshan formation (Q_{1pj}), Baitoushan formation (Q_{2b}), and Cenozoic Holocene Bingchang formation (Q_{4bc}). The lithology of the Laoling formation (Pt_{1z}) is dolomitic marble, with an average thickness of 467 m, the lithology of the Changbai formation (T_{3c}) is rhyolite and rhyolitic pyroclastic rocks and the average thickness is 1300 m, the lithology of the Junjianshan formation (Q_{1pj}) is basalt and olivine basalt and the average thickness is 189 m, the lithology of the Baitoushan formation (Q_{2b}) is trachyte and tuffaceous trachyte and the average thickness is about 130 m, and the lithology of the Bingchang formation (Q_{4bc}) is alkaline pumice and the average thickness is about 51.5 m (Figure 1).

The bedrock geology is composed of ancient metamorphic rocks, formed in the Archean-Proterozoic, and massive granite formed in the Mesozoic. The terrigenous sediments were deposited in the Mesozoic, which was interrupted by intermediate to acid magmatic activities. In the Cenozoic, basalt magma was discharged from the upper mantle via the huge fault which led to the volcanic eruption and created a broad basalt platform. The Tianchi volcano region was the center of those volcanic activities. The bedrocks of the Julong hot springs are dolomitic marble of Laoling formation (Pt_{1z}) and rhyolite of Changbai formation (T_{3c}). The bedrocks of the Jinjiang hot springs are andesite of Changbai formation (T_{3c}) (Figure 2).

3. Methods

3.1. Hot Spring Sample and Analysis. The Julong hot springs and Jinjiang hot springs were sampled in October of 2015 and analyzed for pH, temperature, electrical conductivity (EC), inorganic chemical composition, metal elements, trace elements, and gas composition. The pH and EC were measured in situ by using a low-range pH/EC tester (Hanna Combo Model HI98129, Beijing Hengtai Ruibo Technology Development Co. Ltd., Beijing, China) [15]. Temperature was measured in situ by thermometer. Bicarbonate concentration was determined by using titration against hydrochloric acid. Sulphate and nitrate concentrations were determined by using a spectrophotometer (V-1300, Macy China Instruments Inc., Beijing, China). Silicate was determined by using potassium fluorosilicate. Chloride ion was estimated by titration against a standard solution of AgNO₃. Sodium, potassium, calcium, and

FIGURE 1: Geological map of the Changbai Mountain area.

K_d Dalizi Fm: sandstone and siltstone	ϵ_3m Mantou Fm: dolomite, siltstone and silty shale
K_q Quanshui Fm: andesite and andesitic agglomerate	ϵ_3j Jianchang Fm: limestone, argillaceous limestone, leopard limestone
K_c Changcai Fm: conglomerate and tuffaceous sandstone	Z_q Qinggouzi Fm: limestone and argillaceous limestone
K_n Xiaonangou Fm: conglomerate and siltstone	Z_b Badaojiang Fm, Wanlong Fm and Qiaotou Fm: limestone, sandstone, quartz sandstone
J_3K Shiren Fm: conglomerate, sandstone and mudstone	Z_w Wanlong Fm: limestone and brecciated tuff
J_1t Tuntianying Fm: andesitic breccia and andesite	Nhd Qiaotou Fm: quartz sandstone and sandy shale
J_1l Linzitou Fm: tuffaceous conglomerate, sandstone and siltstone	Nha Nanfen Fm: shale and tuff
J_2-3g Guosong Fm: conglomerate, sandstone and andesite	Nhd Diaoyutai Fm: quartz sandstone
J_2x Xiaodonggou Fm: sandstone and conglomerate	P_3z Zhangsangou Fm: hornblende schist and plagioclase amphibolite
J_2y Yihe Fm: tuffaceous conglomerate and sandstone	P_1l Linjiang Fm: sericite, chlorite quartz schist and phyllite
ϵ_3x Xiaohoukou Fm: Conglomerate and sandstone	P_1dl Dalizi Fm: silk mica schist and thin marble
T_3t Tuopangou Fm: breccia tuff, tuffaceous breccia, andesite	P_1z Zhenzhumen Fm: dolomitic marble
T_3c Changbai Fm: rhyolite, rhyolitic pyroclastic rock and andesite	P_3x Xinnongcun Fm: quartz and feldspar quartzite
F_3m Sunjiagou Fm: mudstone and silty mudstone	P_1h Huangchagou Fm: marble and slate
F_3s Shihezi Fm: Shale and sandstone	P_1m Mayihe Fm: plagioclase amphibolite and schist
C_3p Shanxi Fm: gravel coarse sandstone, coarse sandstone and fine sandstone	Ar_3l Guandian Fm: plagioclase amphibolite
C_3b Benxi Fm and Taiyuan Fm: sandstone and siltstone and shale	Ar_3l Jinan Fm: quartzite
O_2m Majiagou Fm: dolomitic limestone and leopard skin limestone	Ar_3l Laoniugou Fm: quartzite and amphibolite
O_2l Yeli Fm and Liangjiashan Fm: dolomitic limestone and bamboo limestone	Ar_3y Yangjiadian Fm: plagioclase amphibolite and gneiss
G_3s Gushan Fm and Chaomidian Fm: siltstone and shale laminated limestone	Ar_3l Sidolazi Fm: plagioclase amphibolite
ϵ_3p Zhangxia Fm: oolitic limestone, thin limestone	Hot spring groups

FIGURE 2: Bedrock geological map of the Changbai Mountain area.

TABLE 1: Concentration of chemistry compositions on hydrogeochemistry simulation (mg/L).

Water samples	T (°C)	pH	K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	HCO ₃ ⁻	SO ₄ ²⁻	Cl ⁻	H ₂ SiO ₃
Rain samples	12.00	8.01	0.31	0.20	9.96	0.19	17.99	3.34	5.26	2.03
Jinjiang springs	48.50	6.77	19.79	258.25	31.45	15.84	787.60	14.86	47.79	176.26
Julong springs	83.00	7.34	19.41	347.39	37.19	3.275	904.01	0.00	114.715	211.715

FIGURE 3: Arrangement diagram of the prospecting lines of the high-density electrical method.

magnesium were determined by flame atomic absorption spectrophotometer (AA-6300, Shimadzu International Trading Ltd., Shimane, Japan). Other metallic and trace elements were also determined by flame atomic absorption spectrophotometer (AA-6300, Shimadzu International Trading Ltd., Shimane, Japan). The analytical precision for ion measurements was determined by calculating the ionic balance error, which is generally within $\pm 5\%$. AquaChem software was used to determine the hydrogeochemical characteristics of spring waters [16].

Gas samples were collected by prevacuum collector method, and the gas samples were collected in the vacuum-packed bag. CO₂, He, H₂, O₂, and N₂ were determined by using a gas chromatograph (SP-3420A, Beijing Beifen-Ruili Analytical Instrument Co. Ltd., China). The ratio value of ³He/⁴He was determined by mass spectrometer (Noblesse SFT).

3.2. Isotope Analysis. Stable isotope δD - $\delta^{18}O$, C isotopes, and noble gas isotopes (Ne, He) of the Julong hot springs and Jinjiang hot springs were detected to determine the sources of geothermal fluids. Two rain and snow water samples collected in the study area were also tested for stable isotope

δD - $\delta^{18}O$. δD - $\delta^{18}O$ were determined by IRM-GC/MS (Agilent 5973, Shimadzu International Trading Ltd., Shimane, Japan); C isotopes were determined by stable isotope mass spectrometer (DELTA plus XP); noble gas isotopes were determined by noble gas isotope mass spectrometer (Noblesse SFT).

3.3. Rock Sample and Analysis. In order to determine the microstructure, element types, and mineral compositions of the rocks of the Julong hot springs and Jinjiang hot springs, four rock samples were precisely determined by scanning electron microscope (JSM-6700F on Windows NT) and X-ray diffraction (XRD, YST-I). For the SEM and EDS analyses, the rock samples are prepared into thin sections, $0.2 \times 0.2 \times 0.03 \text{ mm}^3$, and for the XRD analysis, the rock samples are prepared into powder.

3.4. Hydrogeochemistry Simulation. Albite, potassium feldspar, pyroxene, silica, calcite, calcium montmorillonite, kaolinite, fluorite, illite, and gypsum possible mineral phases were selected to analyze the source of hot spring chemical compositions. The geochemical modelling programme PHREEQC [17] was used to calculate the possibility of mineral reaction in the Julong and Jinjiang hot spring water. The

FIGURE 4: Distribution of MT station at the volcanic area in Changbai Mountain [21].

rain water samples were selected as the starting point of the reaction path. The Julong and Jinjiang hot spring water samples were selected as the ending point of the reaction path. The pyroxene hydrolysis equation was added in the PHREEQC database. And the uncertainty of the hydrogeochemistry simulation model is 0.05. The concentration of chemistry compositions on the hydrogeochemistry simulation is as shown in Table 1.

3.5. Geophysical Exploration. Geophysical exploration together with the geological and geochemical investigation could successfully establish the existence of geothermal anomaly and the presence of shallow reservoir features. Geophysical methods are very useful, if not essential, in deciphering the geological structures, such as the high-density resistivity (HDRT) method and magnetotelluric (MT) method.

Electrical prospecting is very important in engineering prospecting and an effective method; the direct current method of the high-density resistivity imaging method is a common method of electrical prospecting [18]. The high-density resistivity method is a kind of array exploration method [19]. The resistivity distribution from electromagnetic surveys is interpreted in terms of water saturation of

rocks, hydrothermal alteration, and presence of hydrated minerals. They are covered by basalt and trachyte on the surface around the Jinjiang hot springs. In order to get more geology information, the high-density resistivity method is used to dissect Jinjiang hot springs. Six prospecting lines were arranged with a length of each line of 590 m. The measuring instrument is the DUK-2 high-density electrical apparatus, and each prospecting line has 60 electrodes with an electrode spacing of 10 m. The arrangement diagram of the prospecting lines are shown in Figure 3.

As a deep geophysical technique, the magnetotelluric (MT) method is being widely used for the assessment of geothermal fields in many regions and is also the most appropriate electromagnetic technique to electrically image the subsurface structures [20]. In geothermal regions, it can provide useful information about the lateral and vertical variation of the resistivity of the subsurface. Qiu et al. [21] also analyzed the volcano magma chamber of the Changbaishan Tianchi volcano. In order to obtain more information on the stratum structure and magma chamber characteristics of Changbaishan Tianchi around the Jinjiang hot springs and Julong hot springs, a 103 km long magnetotelluric sounding prospecting line was arranged in Changbaishan with the direction of NE10°. The point of magnetotelluric sounding prospecting was 41 whose dot pitch was 2.5 km (Figures 3 and 4).

In short, we present a multidisciplinary method including hydrogeochemistry, gas geochemistry, whole-rock geochemistry, stable isotope geochemistry, noble gas geochemistry, and geophysical exploration for understanding the hydrogeochemical characteristics and genesis of hydrothermal systems near the active Tianchi volcano (Changbaishan). The flow chart of the study is shown in Figure 5.

4. Results and Discussion

4.1. Hydrogeochemical Characteristics. The values of pH for the Jinjiang hot springs and Julong hot springs ranged from 6.63 to 7.05 (average value 6.77) and from 7.33 to 7.34 (average value 7.335), respectively. The values of temperature for the Jinjiang hot springs and Julong hot springs were from 36.0 to 58.0°C (average value 48.5°C) and from 82.0 to 84.0°C (average value 83.0°C), respectively. The temperatures of the Julong springs were higher than those of the Jinjiang hot springs, and all the hot springs belong to low-temperature geothermal resources.

The values of EC for the Jinjiang hot springs and Julong hot springs were 900–1400 $\mu\text{m}/\text{cm}$ (average value 1150 $\mu\text{m}/\text{cm}$) and 1398–1400 $\mu\text{m}/\text{cm}$ (average value 1399 $\mu\text{m}/\text{cm}$), respectively. The values of total dissolved solids (TDS) for the Jinjiang hot springs and Julong hot springs were 1000.13–1708.77 mg/L (average value 1247.68 mg/L) and 1470.53–1471.79 mg/L (average value 1471.16 mg/L), respectively.

The thermal spring samples were also enriched with trace elements such as H_2SiO_3 and Sr. The concentration of H_2SiO_3 of the Jinjiang hot springs and Julong hot springs ranged from 136.66 mg/L to 232.28 mg/L (average value 176.26 mg/L) and 211.5 mg/L to 211.93 mg/L (average value 211.715 mg/L), respectively. The concentrations of Sr of the Jinjiang hot springs and Julong hot springs ranged

FIGURE 5: Distribution of MT station at the volcanic area in Changbai Mountain.

from 0.029 to 0.062 mg/L (average value 0.043 mg/L) and 0.067 mg/L to 0.089 mg/L (average value 0.078 mg/L), respectively. The types of thermal spring samples were silicate type and silicate-Sr type. The concentrations of hydrochemical data are shown in Table 2.

The distribution of ions of thermal spring samples are plotted on a Piper diagram (Figure 6). It was clearly seen that thermal spring samples were enriched in Na and HCO_3 and were depleted in Cl. The thermal springs were all Na- HCO_3 water type.

The main gas compositions of the Jinjiang hot springs and Julong hot springs are CO_2 , N_2 , and CH_4 (Tables 3 and 4). The percentage of CO_2 of the Jinjiang hot springs and Julong hot springs is 92.25%–93.82% (average value 92.96%) and 93.47%–93.54% (average value 93.47%), respectively, which are both higher than 90%. The average percentage of N_2 of the Jinjiang and Julong hot springs is 5.16% and 5.00%, respectively, and the average percentage of CH_4 of the Jinjiang and Julong hot springs is 1.57% and 0.29%, respectively. Gases associated with mantle magmatic activity include CO_2 , He, CH_4 , and H_2 , especially CH_4 and He [22]. The average percentages of CO_2 , He, CH_4 , and H_2 in the Jinjiang hot springs and Julong hot springs were, respectively, 94.613% and 93.818%, and the average percentages of He and CH_4 in these two hot springs were 1.575% and 0.291%, respectively, which indicated that the released quantity of gases related to magmatic activity of the Jinjiang hot springs is a little higher than that of the Julong hot springs. There is a rule that CO_2 release quantity from thermal springs is higher in volcanic activity and fault areas, and CO_2 as an important geochemical indicator predicts the activity degree

of magmatic and earthquake activity [23]. So the gas origins of the Jinjiang and Julong hot springs are related to magmatic activity. The average percentage of He of the Jinjiang and Julong hot springs is both 0.0015%. The concentrations of He of the Jinjiang and Julong hot springs are relatively stable except for 2003 which was a seismic activity period [24]. A lot of abiogenic CH_4 is also released in the magmatic lava area [25]. The concentration of CH_4 of the Julong hot springs is relatively stable, but those of Jinjiang hot springs are slowly rising in the past years [26].

4.2. Sources of Hot Springs

4.2.1. Recharge Sources of Hot Springs. Figure 7 shows the relationship of $\delta^{18}\text{O}$ - δD of the hot spring samples. The relationship of $\delta^{18}\text{O}$ - δD of snow and rain water samples is fall in the Changbai Mountain meteoric water line, which shows the reliability of water sample test results. The Jinjiang and Julong hot spring water samples all fall in the Changbai Mountain meteoric water offline and nearly along the global meteoric water line. Those characteristics of $\delta^{18}\text{O}$ - δD of the Jinjiang and Julong hot springs show the recharge sources from atmospheric precipitation, which are also influenced by evaporation. There was an ^{18}O drift phenomenon of the hot spring samples, but the amount of drift is only about 1‰. The ^{18}O drift phenomenon has correlation to oxygen isotope exchange between deep geothermal water and silicate [27]. Because ^{18}O in silicate is richer than in geothermal water, the ^{18}O exchange between geothermal water and silicate can make the ^{18}O rise in geothermal water, especially in high-temperature geothermal water.

TABLE 2: Hydrochemical data of the hot spring water samples (in mg/L except for T, pH, and EC. the units of Temp and EC are °C and $\mu\text{m}/\text{cm}$, respectively).

Spring group	ID	Temp	pH	EC	K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	HCO ₃ ⁻	CO ₃ ²⁻	Cl ⁻	SO ₄ ²⁻	F ⁻	NO ₃ ⁻	TDS	H ₂ SiO ₃	Fe
Jinjiang hot springs	WQ1	36.0	6.65	900	13.48	168.70	31.89	19.33	603.95	0	30.67	16.98	3.44	5.0	1000.13	136.66	1.57
	WQ2	45.0	7.05	1200	21.94	284.30	30.12	11.81	827.53	0	53.50	21.23	4.61	0.0	1034.88	157.20	0.63
	WQ3	55.0	6.76	1100	19.56	235.10	30.12	16.11	752.03	0	47.79	0.00	3.98	4.0	1246.94	178.91	0.63
	WQ4	58.0	6.63	1400	24.19	344.90	33.66	16.11	966.89	0	59.20	21.23	4.84	5.0	1708.77	232.28	0.47
	Average value	48.50	6.77	1150	19.79	258.25	31.45	15.84	787.60	0	47.79	14.86	4.22	3.5	1247.68	176.26	0.83
Julong hot springs	WQ5	82.0	7.33	1398	19.40	347.38	37.18	3.33	905.00	0	115.00	0.00	5.33	0.0	1470.53	211.50	0.35
	WQ6	84.0	7.34	1400	19.42	347.40	37.20	3.22	903.02	0	114.43	0.00	5.10	0.0	1471.79	211.93	0.39
	Average value	83.0	7.335	1399	19.41	347.39	37.19	3.275	904.01	0	114.715	0.00	5.215	0.0	1471.16	211.715	0.37
Spring group	ID	Li	Sr	Iodide	Zn	Se	Cu	As	Hg	Cd	Cr	Pb	Mn	Al	Ag	H ₃ BO ₃	
Jinjiang hot springs	WQ1	0.004	0.029	0.004	0.0182	0.0001	0.0055	0.0009	0	0	0.0009	0.0023	0.003	0.48	0.0002	0.0532	
	WQ2	0.001	0.055	0.006	0.0107	0.0000	0.0009	0.0003	0	0	0.0003	0.0010	0.003	0.18	0.0000	0.0225	
	WQ3	0.177	0.027	0.007	0.0008	0.0005	0.0061	0.0026	0	0	0.0007	0.0013	0.010	0.15	0.0006	0.4499	
	WQ4	0.488	0.062	0.007	0.0125	0.0012	0.0188	0.0419	0	0	0.0009	0.0017	0.103	0.25	0.0009	1.3950	
	Average value	0.168	0.043	0.006	0.011	0.0000	0.0080	0.0110	0.	0	0.0010	0.0020	0.029	0.262	0.000	0.480	
Julong hot springs	WQ5	0.000	0.067	<0.002	0.0033	0.0003	0.0001	0.0004	0	0	0.0002	0.0015	0.001	0.08	0.0005	0.0000	
	WQ6	0.000	0.089	0.007	0.0038	0.0002	0.0005	0.0004	0	0	0.0006	0.0011	0.002	0.07	0.0003	0.0125	
	Average value	0.000	0.078	0.007	0.0040	0.000	0.000	0.0000	0	0	0.000	0.001	0.001	0.073	0.000	0.006

FIGURE 6: Piper diagram of sampled spring water.

TABLE 3: The main gas compositions of hot spring water samples (%).

Spring group	ID	He	H ₂	O ₂	N ₂	CH ₄	CO ₂
Jinjiang hot springs	WQ1	0.0105	0.0165	0.35	5.76	1.61	92.25
	WQ2	0.0098	0.2908	0.10	4.55	1.53	93.52
	WQ3	0.000098	0.00291	0.10	4.55	1.53	93.82
	WQ4	0.000105	0.0017	0.35	5.76	1.61	92.28
	Average value	0.0051	0.078	0.23	5.16	1.57	92.96
Julong hot springs	WQ5	0.0015	0.0295	1.23	4.95	0.25	93.54
	WQ6	0.0015	0.0050	1.14	5.05	0.33	93.47
	Average value	0.0015	0.017	1.185	5.00	0.29	93.51

The amount of ¹⁸O drift is small in the study area which confirms that the springs in the study area belongs to low temperature geothermal water.

4.2.2. Gas Sources of Hot Springs. The $\delta^{13}\text{CO}_2$ values of the Jinjiang and Julong hot springs are -1.20‰ , -3.90‰ ,

-2.78‰ , -3.19‰ (average value -2.77‰); -1.20‰ , and -3.90‰ (average value -2.55‰). The $\text{CO}_2/{}^3\text{He}$ values of the Jinjiang and Julong hot springs are 0.76×10^9 , 1.49×10^9 , 1.65×10^9 , 0.96×10^9 (average value 1.22×10^9); 321.90×10^9 , and 18.90×10^9 (average value 170.40×10^9). The different sources of carbon have different carbon isotope

TABLE 4: Gas isotope (carbon and helium) characteristics of the Jinjiang and Julong hot springs.

Spring group	ID	$^3\text{He}/^4\text{He}/10^{-6}$	$^{20}\text{Ne}/^4\text{He}$	$\text{CO}_2/^3\text{He}/10^9$	$\delta^{13}\text{C}_{\text{PDB-CO}_2}$ (‰)	$\delta^{13}\text{C}_{\text{PDB-CH}_4}$ (‰)
Jinjiang hot springs	WQ1	8.97	2.11	0.76	-1.20	-29.40
	WQ2	9.30	0.31	1.49	-3.90	-28.50
	WQ3	5.50	0.20	1.65	-2.78	-28.70
	WQ4	5.93	0.30	0.96	-3.19	-27.54
	Average value	7.43	0.73	1.22	-2.77	-28.54
Julong hot springs	WQ5	2.18	2.11	321.90	-1.20	-19.80
	WQ6	6.27	0.31	18.90	-3.90	34.80
	Average value	4.23	1.21	170.40	-2.55	7.50

FIGURE 7: Relationship of $\delta^{18}\text{O}$ - δD of the hot spring samples.

values. The $\delta^{13}\text{CO}_2$ values of the upper mantle ranged from -9.0‰ to -4.0‰ (average value -6.5‰); the $\delta^{13}\text{CO}_2$ values of earth's crust carbon from marine carbonate sediments are about 0‰ , while those of organic sediments ranged from -40‰ to -20‰ [28]. The different sources of geological fluid also have different $\text{CO}_2/^3\text{He}$ values. The $\text{CO}_2/^3\text{He}$ values of the mantle fluid ranged from 10^8 to 10^{10} , while those of the earth's crust fluid ranged from 10^{10} to 10^{12} [29]. So the carbon sources of the Jinjiang hot springs and Julong hot springs were the upper mantle and may have been influenced by marine carbonate sediments. The sources of ^4He on the earth are radioactively decayed by ^{238}U , ^{235}U , and ^{232}Th in the geological history process. ^3He is almost produced by the mantle. The values of $^3\text{He}/^4\text{He}$ caused by the atmosphere, earth's radioactive crust, and upper mantle are, respectively, 1.39×10^{-6} (1 Ra), $0.0139 \times 10^{-6} \sim 0.139 \times 10^{-6}$ (0.01 Ra~0.1 Ra), and 11.12×10^{-6} (8 Ra) (Allard et al., 1997). The values of $^{20}\text{Ne}/^4\text{He}$ and $^3\text{He}/^4\text{He}$ of the Jinjiang hot springs are 2.11, 0.31, 0.20 and 0.30 (average value 0.73), 8.97×10^{-6} , 9.30×10^{-6} , 5.50×10^{-6} , and 5.93×10^{-6} (average value 7.43×10^{-6}). The values of $^{20}\text{Ne}/^4\text{He}$ and $^3\text{He}/^4\text{He}$ of the Julong hot springs are 2.11 and 0.31 (average value 1.21), 2.18×10^{-6} , and 6.27×10^{-6} (4.23×10^{-6}), which

indicated that the gas sources of the Jinjiang hot springs and Julong hot springs were from the upper mantle.

4.2.3. Hydrogeochemical Composition Sources of Hot Springs

(1) *Mineral Compositions of Rocks.* The chemical composition percentage of the rock samples around the Jinjiang and Julong hot springs is shown in Table 5. The main chemical compositions are SiO_2 , TiO_2 , and Al_2O_3 . The content percentage of SiO_2 of D1 and D2 is about 50%, and those of D3 and D4 are more than 50%. By volcanic rock TAS classification, D1 and D2 belong to trachybasalt and D3 and D4 belong to trachyte.

The surface structure and mineral compositions of the rock samples were analyzed by scanning electron microscope (SEM), energy dispersive spectrum (EDS), and diffraction of X-ray (XRD) methods. Figure 8 shows that the dominant minerals of rock samples were plagioclase with the dominant elements of Na, Al, Si, and O. There are some pyroxene and potassium feldspar, whose dominant elements are, respectively, Ca, Mg, Al, Si, and O and K, Al, Si, and O. Figure 9 shows main minerals through the X-ray diffraction method. The dominant minerals of rock samples D1, D2, D3, and D4 are plagioclase, quartz, chlorite, and pyroxene; plagioclase, quartz, feldspar, pyroxene, chlorite, calcite, and dolomite; plagioclase, feldspar, and pyroxene; and plagioclase, pyroxene, and feldspar, respectively. There are some differences about the results of mineral compositions of rock samples by scanning electron microscope (SEM), energy dispersive spectrum (EDS), and diffraction of X-ray (XRD) methods. The reason is that scanning electron microscope (SEM) and energy dispersive spectrum (EDS) determine the mineral compositions through one point of the rock samples, while X-ray diffraction determines the mineral compositions through whole rock powder samples. Through mineral composition analysis, the main mineral compositions are plagioclase, quartz, and pyroxene, as well as chlorite, calcite, fluorite, gypsum, and dolomite.

(2) *Hydrogeochemical Composition Sources.* Table 6 shows the results of hydrogeochemical simulation. The chemical compositions of the Jinjiang and Julong hot springs are mainly controlled by mineral hydrolysis of albite, potassium feldspar, calcium feldspar, and pyroxene. In the reaction path I (rain to the Jinjiang hot springs), the dissolving

TABLE 5: Chemical composition percentage of rock samples around the Jinjiang and Julong hot springs.

Sample no.	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅
D1	47.76	13.80	10.38	3.19	2.22	9.95	7.83	1.81	0.17	47.76	13.80
D2	51.53	15.41	11.26	3.69	1.98	4.62	7.60	2.11	0.16	51.53	15.41
D3	67.97	13.23	5.41	4.76	5.40	0.88	0.10	0.08	0.16	67.97	13.23
D4	62.37	16.53	6.41	4.94	5.44	1.82	0.53	0.43	0.17	62.37	16.53
Average value	57.41	14.74	8.36	4.15	3.76	4.32	4.02	1.11	0.16	57.41	14.74

FIGURE 8: Scanning electron microscopic (SEM) and energy dispersion spectrum (EDS) diagrams of rock samples.

minerals are albite, potassium feldspar, calcium feldspar, pyroxene, dolomite, and gypsum. The maximum hydrolysis minerals are calcium feldspar and pyroxene with the hydrolysis amounts as $1.24E+02$ and $6.74E+01$, respectively. In the reaction path II (rain to the Julong hot springs), the dissolving minerals are albite, potassium feldspar, calcium feldspar, pyroxene, and dolomite. The maximum hydrolysis minerals are also calcium feldspar and pyroxene with the hydrolysis amounts as $4.41E+02$ and $5.52E+01$, respectively. The hot spring hydrogeochemical compositions are mainly composed of feldspar and pyroxene mineral hydrolysis.

4.3. Stratum Structure and Volcanic Magma Chamber. The data of the high-density resistivity method is inversed by Swedish RES2DINV processing software (Figure 10). The apparent resistivity values are ranged from $10\Omega.m$ to $10,000\Omega.m$. In the six prospecting lines, high-resistance media are mainly distributed in the surface between 40 and 50 m, which includes Cenozoic basalt and trachyte. There is a wide range of the low-resistance zone below the surface of 50 m in the six prospecting lines, which includes volcanic breccia, sand, and gravel. There is a clear boundary line between the low-resistance zone and the high-resistance zone, which infers a fracture. The low-resistance zone is

FIGURE 9: Diagram of X-ray diffraction of rock samples.

mainly a geothermal reservoir and aquifer. So the cap rocks of the Jinjiang hot springs are composed of trachyte, basalt, andesite, and andesitic tuff; the geothermal reservoir is a

fracture zone with the lithology of volcanic breccia, sand, and gravel.

The results of the magnetotelluric (MT) method are 2D inverted by NLG 2D inversion technique (Figure 11). There is an obvious vertical volcano magma channel at the bottom of the Changbai Mountain Tianchi crater, and the magma channel is closed at the depth of about 5–8 km. At the bottom of the crater, near the north direction about 7 km deep, there exists an obvious low-resistance body where the resistivity is less than $10 \Omega \cdot m$ and is connected to the magma channel. It is inferred that it may be a developing magma chamber in a shallow surface. The abnormal region is between stations EC07 and EC09 near the entrance gate of Changbai Mountain, and between EC04 and EC05 stations, there are two obvious nearly vertical low-resistivity zones existing at the depth of about 7–17 km, and connecting with the low-resistance body directly below, it is inferred that the low-resistivity zone contains the magma. As the depth increases, the crust low-resistivity anomaly bodies are widely developed at the depth of 13 km to 30 km north to the position of 20 km south from the Tianchi volcano, which may be the active magma chamber. So there is a magma chamber below the Tianchi volcano.

4.4. Hot Spring Genesis Conceptual Model. The genetic model for the Jinjiang hot springs is as follows: the heat source is a magma body below the north of the Changbai Mountain Tianchi crater with a distance of 7–17 km [30, 31]. And the heat is migrated in the form of thermal conduction manner. The cap rocks are composed of trachyte of Baitoushan formation, basalt of Junjianshan formation, andesite of Changbai formation. The geothermal reservoir is a fracture zone with the lithology of volcanic breccia, sand, and gravel. Hot spring water is mainly supplied by precipitation and is also influenced by evaporation. The Jinjiang hot springs are exposed on the surface along the fault zone by deep circulation with a distance of 4.00–4.56 km. In deep circulation, the hydrolysis of feldspar and pyroxene produces chemical compositions, and the gas compositions are derived from the mantle (Figure 12).

The genetic model for the Julong hot springs is as follows: the heat source is also the magma body. And the heat is also migrated in the form of a thermal conduction manner. The cap rocks are composed of trachyte of Baitoushan formation, basalt of Junjianshan formation, and andesite of Changbai formation. The geothermal reservoir is a fracture zone with the lithology of volcanic breccia and marble. Hot spring water is mainly supplied by precipitation and is also influenced by evaporation. The Julong hot springs are exposed on the surface along the fault zone by deep circulation and heated by the magma heat source. In deep circulation, the hydrolysis of feldspar and pyroxene produces chemical compositions, and the gas compositions are derived from the earth's radioactive crust (Figure 13).

5. Conclusions

The temperatures of the Jinjiang hot springs and Julong hot springs were from 36.0 to $58.0^\circ C$ (average value $48.5^\circ C$) and

TABLE 6: The results of the hydrogeochemical simulation.

Reaction path	Albite	Potassium feldspar	Calcium feldspar	Pyroxene	Quartz	Calcite
I	+2.16E - 02	+3.32E - 04	+1.24E + 02	+6.74E + 01	/	-3.61E + 02
II	+1.73E - 02	+3.40E - 04	+4.41E + 02	+5.52E + 01	/	-9.93E + 02
Reaction path	Dolomite	Gypsum	Kaolinite	Gibbsite	Ca montmorillonite	Chlorite
I	+1.81E - 04	+5.63E - 03	-7.86E + 01	/	-6.36E + 01	-4.96E + 01
II	+4.97E - 04	-7.26E - 04	-3.31E + 02	/	-2.68E + 02	-1.10E + 02

“+” represents minerals dissolving, “-” represents mineral precipitation, and “/” represents no reaction.

FIGURE 10: The results of high-density resistivity method (HDRT).

FIGURE 11: Two-dimensional MT inversion result at the volcanic area in Changbai Mountain (Qiu, 2014).

FIGURE 12: The genesis conceptual model of the Jinjiang hot springs.

FIGURE 13: The genesis conceptual model of the Julong hot springs.

from 82.0 to 84.0°C (average value 83.0°C), respectively. All the hot springs belong to low-temperature geothermal resources. The water chemical types of hot spring water were Na-HCO₃, with high concentrations of Na⁺ and HCO₃⁻ and enriched in trace elements such as H₂SiO₃ and Sr. The main gas composition of the Jinjiang hot springs and Julong hot springs is CO₂, N₂, and CH₄. The recharge sources of hot springs are atmospheric precipitation and are also influenced by evaporation, and the chemical compositions are produced by feldspar and pyroxene mineral hydrolysis. The gas composition sources of the Jinjiang and Julong hot springs are derived from the upper mantle.

The genetic model for the Jinjiang hot springs and Julong hot springs are as follows: the heat source of both is the magma body below the north of the Changbai Mountain Tianchi crater with a distance of 7–17 km. The heat is migrated in the form of a thermal conduction manner. The cap rocks are both composed of trachyte of Baitoushan formation, basalt of Junjianshan formation, and andesite of Changbai formation. The geothermal reservoir is a fracture zone with the lithology of volcanic breccia, sand, and gravel and volcanic breccia and marble, respectively.

Data Availability

The measured data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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