Research Article

Geological and Geochemical Characteristics of the Geothermal Resources in Rucheng, China

Xiting Long,1,2,3,4 Heping Xie,1,2 Xinpeng Deng,3 Xiangyue Wen,1,2 Jian Ou,3 Renwen Ou,3 Jun Wang,1,2 and Fei Liu1,2

1Guangdong Provincial Key Laboratory of Deep Earth Sciences and Geothermal Energy Exploitation and Utilization, Shenzhen Clean Energy Research Institute, College of Civil and Transportation Engineering, Shenzhen University, Shenzhen 518060, China
2Shenzhen Key Laboratory of Deep Underground Engineering Sciences and Green Energy, Shenzhen University, Shenzhen 518060, China
3The 402 Team, The Bureau of Geology and Mineral Resources Exploration of Hunan, Changsha 410014, China
4Sichuan University, State Key Lab of Hydraulics and Mountain River Engineering, Chengdu 610065, China

Correspondence should be addressed to Fei Liu; feiliu182@163.com

Received 13 May 2021; Accepted 14 August 2021; Published 8 September 2021

Academic Editor: Dawei Hu

Copyright © 2021 Xiting Long et al. Exclusive Licensee GeoScienceWorld. Distributed under a Creative Commons Attribution License (CC BY 4.0).

The development of geothermal energy promotes the changing of energy consumption structure in China. A series of experiments were performed to evaluate the geothermal resources of Rucheng County, which is the largest geothermal field in Central South China. The experiments include geothermal exploration, apparent resistivity, and determining the geochemical characteristics of the geothermal water. The experimental results show that the F3 fault zone and F1 hanging wall secondary fault are the main thermal control, heat conduction, water diversion, and thermal storage structures. The pH, EC, and Eh of the river water, shallow groundwater, and geothermal water exhibit seasonal changes. The pH and EC of the geothermal water are higher than those of the river water and shallow groundwater, while the Eh is lower. In addition, the corrosivity coefficient $K_k$ and the Ryznar index are used to evaluate the corrosivity and calcium carbonate scaling of the geothermal water, and it is found that the geothermal water has no corrosiveness or calcium carbonate scaling, which indicates that the geothermal energy in Rucheng County has wide application prospects.

1. Introduction

The development of clean energy not only meets the demand of human development but also alleviates the climate crisis brought from fossil energy use, such as coal and oil [1–3]. Many countries have committed to researching and developing new energy sources, including renewable energy such as solar, wind, biomass, and geothermal [4–7]. In recent years, there has been a rapid development trend for geothermal energy [8–12]. The favored geothermal energy can be used not only for power generation and heating but also for industrial, medical, bathing, and breeding needs. However, geothermal resources should be reasonably assessed and moderately exploited. For example, the Beijing Xiaotangshan Hot Spring belongs to a basin-type geothermal system, which severely limits the geothermal water supply and drops the water level of the geothermal system at a rate of 2 m per year [13]. China has abundant geothermal resources that account for approximately 7.9% of the total world energy production, and the geothermal resource distribution has regional characteristics [14]. Southern Tibet, western Sichuan, and western Yunnan are the primary high-temperature geothermal resources, and the distribution of low- and medium-temperature geothermal resources is more widespread throughout China.

Geochemical methods are often used to analyze the properties of geothermal water and evaluate its development potential. For example, Luo et al. [15] found that the
development potential of southern Kangding is greater than that of northern Kangding by using hydrogeochemistry, stable isotopes, geothermometry, and radiocarbon dating. Long et al. [16] combined geochemical analysis and isotope measurement to identify the groundwater model of deep circulation. It is also found that the circulation convection of groundwater depth exists in the mountainous area where the water conducting fault is well combined with the water blocking fault. Similarly, Şener and Baba [7] monitored the chemical and isotopic compositions of hot springs and geothermal fluids in the Kozakl area throughout the year, and the results showed that the geothermal fluids were formed by local recharge and deep circulation of flowing water. Previous studies have greatly promoted the application of geochemistry in the field of geothermal development. However, it is rare to systematically evaluate the exploitation potential of a geothermal field by using borehole temperature measurement, the audio frequency magnetotelluric method, and the geochemical method to speculate the main thermal control, heat conduction, water diversion, and heat storage structures of geothermal water and to analyze the corrosiveness and scaling capacity of geothermal water. The region of interest for this work is Rucheng County, which is a typical medium-temperature geothermal field in China and is the largest geothermal field in the six provinces of the central and southern regions (Henan, Hubei, Hunan, Guangxi, Guangdong, and Hainan). The geothermal anomaly area of Rucheng County reaches 300 hectares with a water temperature that is generally 91.5°C and a maximum of 98°C. To date, Rucheng County has.
developed hot spring medical services at the springs of Rucheng, Luoquan, Tangkou, Datang, Tangei, Tongkeng, etc. in addition to agriculture and aquaculture. To further explore the geothermal resources of Rucheng County and address the energy demand, we have performed in-depth geothermal resource exploration in the Reshuiwei of Rucheng County since 2017. The characteristics of geothermal change in the Reshuiwei area of Rucheng County are explored here using borehole temperature measurements. Section 2 introduces the geological and tectonic setting of the study area. Section 3 introduces the testing equipment and methods of well temperature measurement, apparent resistivity, and geochemistry. Section 4 introduces the test results and data analysis. The geochemical characteristics of geothermal water, shallow groundwater, and river water in the study area were revealed, and the scaling and corrosiveness of geothermal water were evaluated. Section 5 summarizes the conclusions of this research.

2. Geological and Tectonic Setting

The exposed strata in the study area are primarily Middle-Lower Cambrian, Sinian shallow metamorphic rock series, and Quaternary, and the magmatic rocks in this area are mainly Yanshanian mica granite. The intrusive time of granite is 141-172 Ma, which is from the Late Triassic to Middle Jurassic. The magmatic rocks are in intrusive contact with the Cambrian and Sinian strata with an uneven contact surface that is mostly zigzag with a relatively gentle incline to the northwest. In addition, the outer contact alteration zone has a width of 200-500 m of the hornstone and quartz hornstone zones. There are fine-grained granite, monzonite, and granite pegmatite dykes in the internal contact zone, which indicates frequent magmatic activity with intensity from strong to weak. The granite diagenetic depth ranges from deep to shallow. After Yanshan’s second and third stages, the diagenetic depth ranges from 10 to 0.5 km. Diagenetic temperature is 693-507°C. The granite has a high content of radioactive elements with average uranium (U) content of 13.5 ppm and average thorium (Th) content of 36.8 ppm. The accessory minerals are apatite and zircon, and the altered minerals include chlorite, sericite, and epidote.

The primary structure in the study area is a fault, while the fold is undeveloped. The structural types include the east-west, Cathaysian, Neocathaysian, and northwest structures, as shown in Figure 1. The east-west structure is distributed in the west and northwest of the study area, which is a tightly closed anticline structure composed of Cambrian and Sinian shallow metamorphic rocks. The axis of the anticline is composed of feldspathic quartz sandstone from the Sinian system. The two limbs of the anticline are Cambrian with exposed lengths of 2 km. The anticline axis runs near
the east-west and is strongly squeezed with an inclination angle of 60-75°. The Huaxia-type faults are composed primarily of F1, F2, F4, F5, F14, F17, F18, F19, and other faults, which are distributed in dense belts and run through the entire area. The belt width of the fault zone is 2-3 km. In the Reshuiwei area, the strike is 45-55°, which is an arc-shaped fault zone protruding northwards. The faults in the fault zone are generally inclined to the northwest with a dip angle that is generally greater than 60°. In addition, the fault zone is an imbricate structure in the section, where calcite, chalcedony, and quartz thin shells can be seen in the fault zone. It is found that the early breccia is broken into new breccia after the later fault activity, which indicates that the Huaxia-type fault has a long-term and multistage fault structure. In the study area, the Neocathaysian structure is developed with a primary structure that is in the northeast (NE) direction with a zonal distribution. Moreover, the Neocathaysian structure includes primarily the F3, F6, and F7 faults. The torsional faults are two groups of torsional structural planes matched with the main faults of the Neocathaysian system. The torsion faults in the north-east (NEE) direction are relatively developed and large-scale, such as the F12 and F9, and the torsion faults in the northwest (NW) direction are the F22, F20, F10, etc.

3. Methods and Materials

3.1. Well Temperature Measurement. The borehole distribution of the tested temperature is shown in Figure 2, which was measured using the HW-III high precision deep-water thermometer with a temperature range of 0-150°C and accuracy of ±0.1°C. The measured depth range of the borehole is 0-3000 m, and the temperature measurements should be performed after the drilling is stopped for 24 hours. Before each measurement, the instrumentation is calibrated using a high-precision mercury thermometer to eliminate systemic errors from the equipment. The probe is carefully inserted, and the temperature is allowed to stabilize (stable for more than 30 s) before recording the measurement.

3.2. Apparent Resistivity Test. The apparent resistivity test uses the EH4 high-frequency magnetotelluric sounding equipment. The test point and line distances are 50 and 100 m, respectively. A total of 200 test points are installed at depths of 100, 200, 300, 400, 500, and 600 m.

3.3. Geochemical Test. To explore the characteristics of the geothermal water circulation system, the physical and chemical parameters of geothermal water, shallow
groundwater, and river water were measured in the study area. The parameters of interest were the water temperature, pH, electrical conductivity (EC), oxidation-reduction potential (ORP), primary ions, and trace elements in the waters. The main cations and anions were tested using an ICP-OES (PerkinElmer, Optima 5300 DV) and ion chromatographer (Shimadzu LC-10ADvp), respectively, and the trace elements were measured with inductively coupled plasma mass spectrometry (PerkinElmer, ICP-MS Elan DRC-e). The sampling locations are shown in Figure 3.

4. Results and Discussion

4.1. Characteristics of Geothermal Field

4.1.1. Vertical Geothermal Characteristics of Borehole. The vertical ground temperature characteristics of the boreholes in the hot water area of Reshui town are shown in Figure 4. The curves can be divided into four types: (1) Water-rich hot water hole: this type of drilling curve inclines to the left longitudinal axis after passing through the fracture zone, and the ground temperature gradient is negative,
which indicates that the floor of the crushing zone has a weak water content and low thermal conductivity. In addition, this drilling curve indicates a large water content and high water temperature and includes ZK1, ZK2, ZK4, and SK4. (2) Medium hot water hole with water content: this curve type does not tend to shift to the left, which indicates that either the borehole did not pass through the fracture zone, there was a steep dip, or the borehole was located beside the steep dip fault. This type of borehole has low water content but large vertical thickness, such as drill holes ZK8, ZK19, ZK16, ZK21, and ZK3. (3) Outer contact zone of the rock mass: this type of curve is approximately a straight line, indicating that the geothermal gradient of the borehole remains nearly the same. A larger slope (ground temperature gradient) indicates thicker cap rock, and the drilling did not reveal the main water-containing fracture zone. Examples include ZK20 and ZK11. (4) Borehole curve of F3 footwall shallow metamorphic rock: this type of drilling curve is close to the longitudinal axis, indicating that the drilling is located in the fracture and alteration zones. Moreover, either the external contact fractures of the rock mass are not developed or most of the fractures are filled in the borehole. This type is characterized with a low temperature and water content, such as ZK17, ZK5, ZK12, and ZK18.

4.1.2. Distribution Characteristics of Geothermal Gradient. Figure 5 shows the average geothermal gradient at a 100 m depth over the entire hole, which is calculated based on the temperature measurement data of 21 boreholes. The temperature gradient of the 100 m depth is more than 30°C in the zone of ZK1-ZK16. The geothermal gradient of the entire hole is greater than 20°C per 100 m, which is located at the connection of boreholes ZK16, ZK15, ZK21, and ZK19.

4.1.3. Spatial Distribution Characteristics of Geothermal Field. Figure 6 shows the isotherms of +300 m, +200 m, +100 m, and ±0 m above sea level. The comparison indicates that the isotherms at various elevations differ significantly. When the elevation is +300 m, the 80°C isotherm is closed within a circle near the ZK1 and ZK4 holes, as shown in Figure 6(a), where the long axis of the isothermal coil is 232 m and the short axis is 98 m. When the altitude is +200 m, the 80°C isotherm is closed within a circle near the ZK1 and ZK6 holes, and the long axis of the isothermal coil is 300 m and the short axis is 77 m, as shown in Figure 6(b). When the altitude is +100 m, there are two areas within the isoline of 80°C. The first is the Reshuwei area where the 80°C isotherm is along the northeast direction (isotherm contains the ZK16 hole), and the long axis is 139 m and the short axis is 67 m. Compared with the altitude for +200 m, the displacement of the isotherm to the southeast is about 130 m, which is shortened by 54%. The second area is from Miaowan to Dongqing village where the 80°C isoline appears between the ZK19 and SK2 holes and is nearly east-west. The temperature shows a trend that is high in the south and low in the north. The isoline of the ground temperature from ±0 m to +60 m above sea level is shown in Figure 6(d). The 80°C isotherm in the southeastern area of Reshuwei inclines to the southeast for 76 m.
Figure 6: Variation characteristics of isotherms at elevations of (a) +300 m, (b) +200 m, (c) +100 m, and (d) ±0 m.
From Miaowan to Dongqing village, the temperature range above 80°C increases significantly and the geothermal gradient increases while the temperature tends to rise along the southeast.

Therefore, the 80°C isothermal column in the Reshuiwei area extends to the southeast. The ZK19 and ZK21 holes in the area from Miaowan to Dongqing can have a high temperature of 80°C at an elevation of +15 m, which indicates that the hot water source is from the F1 fault zone. The heat conduction structure is the second imbricate fracture zone of the hanging wall for the F1 fault.

4.1.4. Geotemperature Profile Characteristics. The fault zone has an important influence on the thermal reservoir structure for the geothermal field. The development of the fault zone in the Reshuiwei geothermal field is observed through the geothermal isoline profile, as shown in Figure 7. The trend of the isoline for the ground temperature alternates between concavity and convexity. The fracture zones of the...
F4, F9, F7, and F12 in the granite body show an upward convex trend; however, the fault zones in the Sinian and Cambrian lens bodies have a downward trend. It is noted that the 90°C isoline has no sealing open curve either upwards or downwards on both sides of the F3 fault zone for the contact zone between the granite body and the Sinian and Cambrian system, which indicates that the F3 and F1 hanging wall secondary faults are the main heat control, heat conduction, water conduction, and heat storage structures in the Reshuiwei geothermal field.

4.2. Apparent Resistivity Test Results. The resistivity of the water-rich fracture zone is generally relatively low. The apparent resistivity at depths of 100, 200, 300, 400, 500, and 600 m is measured using the audiofrequency magnetoTelluric method (EH4). The contour map of the apparent resistivity horizontal section is shown in Figure 8. The blue (red) color indicates a low (high) apparent resistivity. The color is nearly blue with an apparent resistivity less than or equal to 1000 Ω as the depth is 100 m. At the same time, the apparent resistivity is distributed in the survey area as a planar shape. With the increased testing depth, the apparent resistivity gradually exhibits an island distribution, and the area of its increases gradually grows, as shown in Figure 8. When the test depths are 500 and 600 m, the low apparent resistivity area in the western region of Reshuiwei disappears, and the red high resistance area (≥4200 Ω) is island-like along the east-west direction. Comparing the changes of the apparent resistivity at different test depths indicates that areas with a low apparent resistivity are distributed primarily in the southeast direction. The verification of the ZK19 borehole in the southeast area shows that the area with low apparent resistivity is a high-temperature area with water content. Therefore, it is inferred that the heat source of the Reshuiwei geothermal field is from the F1 fault zone and along the southeast.

4.3. Hydrochemical Characteristics. The geochemical method is helpful for the exploration of groundwater circulation systems [16]. The pumping test of boreholes G02 (SK3), G05, G06 (ZK8), G07, G15, G16, and G17 shows that the pH, EC, and ORP of geothermal water have seasonal changes. At the same time, there are significant differences in the chemical properties between geothermal water, river water, and shallow groundwater. Figures 9(a) and 9(b) show the relationships between the EC, Eh, and pH for geothermal water, river water, and shallow groundwater during summer. The pH of geothermal water is higher than that of shallow groundwater and river water, which is alkaline, as shown in Figures 9(a) and 9(b). However, the pH of shallow...
groundwater is lower than that of river water, which is weakly acidic. The EC is affected by the soluble salt content in water. The ECs of the shallow groundwater and river water are lower than that of geothermal water. The average ECs of shallow groundwater and river water are lower than 60 μs per cm and 40 μs per cm, respectively. However, the maximum EC of geothermal water is approximately 350 μs per cm. In addition, the Eh values of the three kinds of water samples also show significant differences. The Eh value of geothermal water is lower than those of river water and shallow groundwater, indicating that geothermal water is in a weak oxidation state.

The Eh value of geothermal water tested during winter is greater than during summer, as shown in Figure 9(d). Nevertheless, seasonal differences in the pH and EC values of geothermal water are not significant. The pH, EC, and Eh values of shallow groundwater increased slightly during winter, while the pH and EC values of river water changed little during winter and the Eh value increased slightly. The pH and EC values of shallow groundwater and river water are lower, and the Eh value is higher, which suggests the area has less soluble minerals. The water circulation depth is shallow and fast, and the high pH and EC values of geothermal water and the low Eh value indicate that the geothermal water has undergone a deep circulation path. The higher temperature of the geothermal water can dissolve and filter more minerals. Moreover, the water circulation speed is slow and the residence time is long in the deep reduction environment, which weakens the water oxidation.

4.4. Evaluation of Corrosiveness and Scaling of Underground Hot Water. Underground hot water is at high temperatures and contains a variety of corrosive chemical components (such as chloride, sulfate, free carbon dioxide, and hydrogen sulfide). These cause severe corrosion damage to geothermal development metal equipment. To explore the corrosivity of underground hot water in the geothermal field of the study area, the corrosion coefficient $K_k$ is defined as [17]

$$K_k = 1.008\left(y\text{H}^+ + y\text{Al}^{3+} + y\text{Fe}^{2+} + y\text{Mg}^{2+} - y\text{HCO}_3^- - y\text{CO}_3^{2-}\right),$$

(1)
\[ K_{k1} = 1 \text{ and } K_{k2}^0 = \gamma_Mg^{2+} - \gamma_HCO_3^-/C_0/C_1, \]

where \( K_{k1} \) and \( K_{k2} \), respectively, represent the acidic and alkaline corrosion coefficients in geothermal water and \( \gamma \) represents the milligram equivalent of the ion content per litre. When the corrosion coefficient \( K_k > 0 \), the geothermal water is corrosive; when \( K_k < 0 \) and \( K_k + 0.503Ca^{2+} > 0 \), it is semicorrosive; and when \( K_k < 0 \) and \( K_k + 0.503Ca^{2+} < 0 \), it is noncorrosive. The evaluation results for the groundwater corrosivity in the Reshuiwei geothermal field are shown in Table 1. The corrosion coefficients \( K_k \) are all less than 0, which indicates that the geothermal water is noncorrosive.

Another important evaluation metric for geothermal water is scaling. The scaling of calcium carbonate in geothermal water will inhibit and damage the well wall, which reduces the efficiency of geothermal energy exploitation. When the chloride ion content in geothermal water is low (<25% mg equivalent), the Ryznar index (RI) dictates the scaling tendency of the calcium carbonate in hot water.

The calculation formula of the RI is shown as follows [18]:

\[ RI = 2pHc - pHa, \]

where \( pHc \) is the calculated pH, \( pHa \) is the actual pH measured in hot water, \( ALK \) is the molar concentration of \( HCO_3^- \) ions in the geothermal water, and \( Ke \) is the temperature-dependent equilibrium constant. The scaling trend standard of geothermal water evaluated from the RI is shown in Table 2. Based on Equations (3) and (4), the RI for the Reshuiwei geothermal fluid is calculated as 11.87-16.73 (>7.0), which suggests that geothermal water does not tend to produce calcium carbonate scaling.

5. Conclusion

This study tested and analyzed the geothermal temperature, apparent resistivity, and chemical characteristics of geothermal water in Rucheng County. The main conclusions are as follows.

(i) It is inferred from the geothermal distribution that the hanging wall secondary fracture zone of F1 and the fault zones of F3 are the primary thermal control, heat conduction, water diversion, and thermal storage structures in the Reshuiwei geothermal field.

(ii) The variation of apparent resistivity in the range of 100-600 m was measured. It is found that the apparent resistivity of the ZK19 borehole in the southeast area is low, which means this area is a high temperature water bearing area. It is inferred that the F1 fault zone in the southeast of Reshuiwei is the heat source.

(iii) There are significant differences in the geochemical characteristics (including pH, EC, and Eh) among the geothermal water, shallow groundwater, and river water. The pH and EC values of the geothermal water are higher than those of the river water and shallow groundwater, while the Eh value is lower.

(iv) Calculating the \( K_k < 0 \) and the RI (11.87-16.73) suggests that the geothermal water of Reshuiwei in Rucheng County is noncorrosive and does not have the tendency towards calcium carbonate scaling.

### Table 1: Evaluation of hot water corrosivity in the Reshuiwei geothermal field.

| Mg\(^{2+}\) (mg/l) | HCO\(_3^-\) (mg/l) | Ca\(^{2+}\) (mg/l) | Kk  | Evaluation results |
|------------------|------------------|-----------------|-----|-------------------|
| 3.8              | 390              | 14.5            | -6.129 | Noncorrosive     |
| 2.12             | 118.1            | 12.3            | -1.7853 | Noncorrosive |
| 0.1              | 3716.081         | 4.8             | -6.1314 | Noncorrosive |
| 0.0              | 112.7            | 4.0             | -1.862 | Noncorrosive    |
| 0.01             | 378              | 4.9             | -6.237 | Noncorrosive |
| 0.01             | 112.7            | 4.5             | -1.8537 | Noncorrosive |

### Table 2: Evaluation criteria for calcium carbonate scaling.

| Ryznar index (RI) | Scaling tendency |
|------------------|------------------|
| <4.0             | Very severe      |
| 4.0-5.0          | Severe           |
| 5.0-6.0          | Moderate         |
| 6.0-7.0          | Slight           |
| >7.0             | None             |

\[ K_{k2} = 1.008(\gamma Mg^{2+} - \gamma HCO_3^{-}) \]

\[ pHe = - \log [Ca^{2+}] - \log [ALK] + Ke, \]

Data Availability

All data generated or analyzed during this study are included in this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by the Guangdong Provincial Department of Science and Technology (No. 2019ZT08G315), Hunan Natural Resources Science and Technology Plan Project.
References

[1] M. Dietrich, J. Huling, and M. P. S. Krekeler, "Metal pollution investigation of Goldman Park, Middletown Ohio: evidence for steel and coal pollution in a high child use setting," *Science of the Total Environment*, vol. 618, pp. 1350–1362, 2018.

[2] J. Hu, Q. Sun, and H. He, "Thermal effects from the release of selenium from a coal combustion during high-temperature processing: a review," *Environmental Science and Pollution Research*, vol. 25, no. 14, pp. 13470–13478, 2018.

[3] R. E. Masto, M. K. Singh, T. K. Rout et al., "Health risks from PAHs and potentially toxic elements in street dust of a coal mining area in India," *Environment Geochemistry and Health*, vol. 41, no. 5, pp. 1923–1937, 2019.

[4] M. Höök, J. C. Li, K. Johansson, and S. Snowden, "Growth rates of global energy systems and future outlooks," *Natural Resources Research*, vol. 21, pp. 23–41, 2012.

[5] A. Kamali-Asl, E. Ghazanfari, N. Perdrial, and N. Bredice, "Experimental study of fracture response in granite specimens subjected to hydrothermal conditions relevant for enhanced geothermal systems," *Geothermics*, vol. 72, pp. 205–224, 2018.

[6] Z. Lyu, X. Song, and G. Li, "An analytical method to determine rock spallation temperature and degree of heterogeneity in thermal spallation drilling for geothermal energy," *Geothermics*, vol. 77, pp. 99–105, 2019.

[7] M. F. Şenener and A. Baba, "Geochemical and hydrogeochemical characteristics and evolution of Kozakli geothermal fluids, Central Anatolia, Turkey," *Geothermics*, vol. 80, pp. 69–77, 2019.

[8] S. Loppi, "Environmental distribution of mercury and other trace elements in the geothermal area of Bagnore (Mt. Amiata, Italy)," *Chemosphere*, vol. 45, no. 6–7, pp. 991–995, 2001.

[9] J. Majorowicz and S. E. Grasby, "Geothermal energy for northern Canada: is it economical?," *Natural Resources Research*, vol. 23, no. 1, pp. 159–173, 2014.

[10] S. A. Mario-César, B. Jochen, and S. Fernando, "Assessment of submarine geothermal resources and development of tools to quantify their energy potentials for environmentally sustainable development," *Journal of Cleaner Production*, vol. 83, pp. 21–32, 2014.

[11] Q. Sun and J. J. Hu, "The effect of rapid cooling on the thermal diffusivity of granite," *Journal of Applied Geophysics*, vol. 168, pp. 71–78, 2019.

[12] B. Ž. Todorović, D. T. Stojiljković, T. P. Pantić et al., "Direct formation of burkeite in the geothermal waters at Vranjska Banja, Serbia," *Natural Resources Research*, vol. 28, no. 4, pp. 1259–1267, 2019.

[13] H. Y. Zhou, X. Zhou, R. Chai, L. Yu, C. H. Liu, and L. P. Li, "Occurrence and evolution of the Xiaotangshan hot spring in Beijing, China," *Environmental Geology*, vol. 53, no. 7, pp. 1483–1489, 2008.

[14] S. Wang, L. M. Jian, Z. H. Shu, S. H. Chen, and L. Y. Chen, "A high thermal conductivity cement for geothermal exploitation application," *Natural Resources Research*, vol. 29, no. 6, pp. 3675–3687, 2020.

[15] J. Luo, Z. Pang, Y. Kong, and Y. Wang, "Geothermal potential evaluation and development prioritization based on geochemistry of geothermal waters from Kangding area, western Sichuan, China," *Environmental Earth Sciences*, vol. 76, no. 9, p. 343, 2017.

[16] X. Long, K. Zhang, R. Yuan, L. Zhang, and Z. Liu, "Hydrogeochemical and isotopic constraints on the pattern of a deep circulation groundwater flow system," *Energies*, vol. 12, no. 3, pp. 404–418, 2019.

[17] D. Liu, *Feasibility study on new groundwater sources in Shuangcheng district of Harbin*, M. Sc. Thesis, Jilin University, Changchun, 2019.

[18] Y. Yu, X. Zhou, and B. Fang, "Judgement and analysis of the scaling trend of thermal groundwater in Beijing's urban geothermal fields," *City geology*, vol. 2, no. 2, pp. 14–18, 2007.