Hydrogeochemical Characteristics and Formation of Low-Temperature Geothermal Waters in Mangbang-Longling Area of Western Yunnan, China

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Numerous low-temperature geothermal waters are distributed extensively in Mangbang-Longling of western Yunnan in China, whose formation mechanism has not been completely investigated yet. This study focused on the hydrogeochemical evolution, reservoir temperature, and recharge origin of geothermal waters using hydrogeochemical and deuterium-oxygen (D-O) isotopic studies. The low-temperature geothermal waters were characterized by HCO3-Na type, while shallow cold spring was of the hydrochemical type of HCO3-Ca. The hydrogeochemical characteristics of low-temperature geothermal waters were mainly determined by the dissolution of silicate minerals based on the geological condition and correlations of major and minor ions. The reservoir temperatures of low-temperature geothermal waters ranged from 111°C to 126°C estimated by silica geothermometry and the silicon-enthalpy graphic method. Low-temperature geothermal waters circulated at the largest depth of 1794–2077 m where deep high-temperature geothermal waters were involved. The data points of δD and δ18O of the hot spring water samples in the study area show a linear right-up trend, indicating the δ18O reaction between the water and rock and a possible mixture of magmatic water from below. The low-temperature thermal waters were recharged by meteoric water at the elevation of 2362–3653 m calculated by δD values. Upwelling by heating energy, low-temperature geothermal waters were exposed as geothermal springs in the fault and fracture intersection and mixed by up to 72% shallow cold waters at surface. Based on acquired data, a conceptual model of the low-temperature geothermal waters in the Mangbang-Longling area was proposed for future exploitation.

1. Introduction

Energy shortage has been the serious problem for human beings globally due to explosive population growth, accelerated industrialization, and developed living standards [1]. Nowadays, the energy supplied for the whole world consists of fossil fuels and renewable energy. It is noted fossil fuels will be consumed in decades, and thus, renewable energy is expected to be the predominate energy in future. Among renewable energy sources, geothermal energy presents large exploring potential and is welcome all over the world [2–4]. The geothermal system with reservoir temperature lower than 150°C at 1000 m depth is clarified as low-temperature geothermal resource [5]. Due to the advantages of universal distribution and general application, low-temperature geothermal resource has been becoming the research hotspot globally [6–12].

Due to the intensive tectono-magmatic evolution, the Himalaya geothermal belt in China is the famous geothermal area for massive geothermal energy, including southern Tibet, western Yunnan, and western Sichuan [13, 14]. Among them, western Yunnan possesses numerous and
widespread high- and low-temperature geothermal waters, representing an outstanding natural laboratory for investigating the genetic mechanism for the geothermal system [15]. Although a wealth of studies concerns the geothermal waters in western Yunnan, the majority was concentrated on the high-temperature geothermal waters in the Rehai and Banglaizhang regions [16–24]. In comparison, low-temperature geothermal waters in adjacent Mangbang-Longling areas have been scarcely analyzed. As a result, it is generally suggested that the high-temperature geothermal waters were heated by the underlying magma chamber and were characterized by the involvement of magmatic contents [25]. In contrast, the genetic mechanism of low-temperature geothermal waters remains controversial and has yet to be further investigated. In addition, the relationship between high-temperature and low-temperature geothermal waters is enigmatic. The imbalanced research for the low-temperature geothermal system seriously hampers the comprehensive exploitation of geothermal resource in western Yunnan.

Therefore, we present hydrogeochemical and isotopic analyses (including major and trace elements, as well as deuterium and oxygen isotopes) for fourteen geothermal waters and one cold spring collected from the Mangbang-Longling area in western Yunnan. This study is aimed to the hydrogeochemical characteristic of geothermal and cold spring waters, clarify water-rock interaction, estimate reservoir temperature, and trace recharge source. Our new findings are expected to construct the genetic mechanism of the low-temperature geothermal system, providing the reference for future management and sustainable exploitation of geothermal resource in the Mangbang-Longling area of western Yunnan.

2. Study Area

The Mangbang-Longling area is situated in western Yunnan, southwestern China (Figure 1). It is typical of subtropical monsoon climate with average annual air temperature of 14.8°C and mean annual rainfall of 1470 mm. The geomorphology is typical of medium-high mountain with the elevations of 900–3800 m. The Longchuan and Daying rivers traverse southwestwardly through the Mangbang-Longling area, fed by several streams.

Tectonically, the Mangbang-Longling area is bordered by the Longling-Ruili fault to the east and the Dayingjiang fault to the west [26]. Due to the subduction of the Neo-Tethyan Ocean and subsequent continental collision, widespread magmatic and hydrothermal activities were developed in the western Yunnan [27–30]. In the study area, the Gaoligong Group metamorphic rocks and Yangshanian granitic rocks are exposed instead of sedimentary strata [31]. Neogene volcanic rocks and Pliocene basaltic rocks are formed as overlying cap rocks. Numerous NNW-NW and NS-trending secondary faults and fractures were developed extensively by continuous India-Asia collision [32]. Abundant secondary faults and fractures provide the permeable way for groundwater circulation. In the study area, groundwater is mainly recharged by precipitation and local runoff. The aquifers consist of carbonate and silicate rocks.

As a considerable segment of Himalaya geothermal belt, western Yunnan reserves abundant geothermal resource [33]. Geothermal waters are mostly exposed in the faults or their intersections (Figures 1 and 2). The temperatures of geothermal waters vary greatly with the range of 20–96°C. High-temperature geothermal waters (hydrochemical type: Cl·HCO3·Na) are mostly assembled in the Rehai and Balazhang area, while low-medium temperature geothermal waters (hydrochemical type: HCO3·Na) are distributed dispersedly in the Mangbang-Longling area.

3. Sampling and Methodology

Fourteen geothermal springs and one cold spring were sampled in the Mangbang-Longling area. Physicochemical parameters of geothermal waters (e.g., temperature, pH, alkalinity, and total dissolved solids (TDS)) were measured in situ using WTW. The concentration of HCO3 was measured using Gran titration. The experiments were conducted in the State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, within one week after sampling. Major cations (e.g., K+, Na+, Ca2+, and Mg2+) were analyzed by inductively coupled plasma-optical emission spectrometry (ICP-OES) (Thermo Fisher ICAP-6300), while major anions (Cl− and SO42−) were determined by ion chromatography (Dionex ICS-1100). Charge balances between major anions and cations were within the error range of ±10%.

The δD and δ18O values were reported in delta (δ) relative to VSMOW (Vienna Standard Mean Ocean Water) using conventional δ (‰) notation. The analytical precision for δD and δ18O was ±0.6‰ and ±0.2‰, respectively.

4. Analytical Results

4.1. Hydrogeochemical Characteristics. The physical properties and chemical compositions of geothermal waters and cold waters in the Mangbang-Longling area are given in Table 1. The exposed temperature and pH values of geothermal waters had a range of 24–57°C and 6.5–7.3, respectively. Na and HCO3 were the primary cation and anion, indicative of the HCO3·Na hydrochemical type (Figure 3). The contents of SiO2, Sr, Li, As, and F were relatively low and constant. In comparison, high-temperature geothermal waters displayed Cl·HCO3·Na hydrochemical type and higher contents of SiO2, Sr, Li, As, and F, indicating involvements of deep magmatic compositions [23].

One cold water sample was analyzed for comparison. Cold water sample was characterized as HCO3·Ca type, according to the hydrogeochemical compositions (Figure 3). The minor contents of SiO2, Sr, Li, As, and F were very low and constant as well.

4.2. Environmental Isotopes. The δ18O and δD compositions (vs. Vienna Standard Mean Ocean Water (VSMOW)) of the geothermal water samples varied from −9.2‰ to −11.1‰ and from −57.8‰ to −78.9‰, respectively. Cold water
sample showed relatively enriched \(\delta^{18}O\) (−8.5‰) and \(\delta^D\) (−56.6‰) compositions than those of geothermal waters.

4.3. Multimineral Saturation Indices. The thermodynamic process of the groundwater system can be clarified by mineral equilibrium calculation, which is helpful to reflect the process of water-rock interaction [14]. Mineral saturation indices (SI) of geothermal waters were calculated for evaluating mineral equilibrium based on discharge temperature and pH. The PHREEQC 3.0 software was carried out to calculate multimineral SI values [35]. In this study, calculated SI values of most selected minerals (excepted chalcedony and quartz) were lower than zero, indicating geothermal water occurs in undersaturated condition. Detailed results are given in Table 2.

5. Discussion

5.1. Processes Controlling the Hydrogeochemical Compositions. CI is characterized as the conservative affinity and hardly altered by water-rock interactions and adsorption...
Table 1: Chemical and isotopic analyses of geothermal water and cold spring samples.

| Sample no. | GS1   | GS2   | GS3   | GS4   | GS5   | GS6   | GS7   | GS8   | GS9   | GS10  | GS11  | GS12  | GS13  | GS14  | CS1   |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| X          | 17467700 | 17466890 | 17466025 | 17458696 | 17452200 | 17452250 | 17453000 | 17461020 | 17453690 | 17458250 | 17464774 | 17455000 | 17452350 | 17467957 | 17466957 |
| Y          | 2751100 | 2753164 | 2752528 | 2754645 | 2762500 | 2761450 | 2761550 | 2753164 | 2761550 | 2740586 | 2736100 | 2732700 | 2753276 | 2760757 |
| Local elevation | 1200 | 1200 | 1270 | 1780 | 1507 | 1670 | 1690 | 1820 | 1720 | 1335 | 1150 | 1390 | 1240 | 1300 | 1200 |
| T          | 28.5 | 24 | 30 | 45.5 | 35 | 36 | 42 | 39 | 51 | 30 | 51 | 53 | 24 | 10 |
| pH         | 6.7 | 6.9 | 7.1 | 7.2 | 7 | 7.2 | 7.3 | 7.1 | 7.2 | 6.5 | 6.8 | 6.5 | 6.5 | 6.5 |
| TDS        | 770 | 530 | 388 | 156 | 196 | 124 | 244 | 138 | 118 | 208 | 868 | 132 | 230 | 97 |
| Flow       | 1.2 | 1.2 | 18.9 | 0.9 | 2.1 | 3.1 | 0.3 | 2.0 | 5.0 | 3.0 | 0.0 | 2.9 | 0.8 | 0.8 |
| K          | 11.7 | 8.8 | 5.5 | 0.6 | 0.7 | 0.8 | 0.5 | 0.6 | 0.7 | 1.5 | 10.2 | 1.1 | 11.9 | 2.0 |
| Na         | 206.0 | 130.0 | 41.9 | 54.9 | 31.7 | 44.4 | 34.6 | 28.4 | 57.9 | 258.0 | 40.3 | 157.6 | 32.0 | 1.8 |
| Ca         | 27.6 | 29.0 | 39.0 | 8.1 | 1.1 | 2.5 | 0.8 | 0.9 | 1.4 | 0.6 | 68.6 | 1.7 | 1.1 | 20.0 |
| Mg         | 28.0 | 15.4 | 21.1 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 9.8 | 0.1 | 0.0 | 2.9 |
| Cl         | 1.9 | 0.4 | 5.4 | 10.2 | 8.9 | 4.8 | 5.8 | 6.8 | 6.3 | 10.1 | 0.1 | 10.2 | 16.3 | 3.8 |
| SO₄        | 1.9 | 0.4 | 5.4 | 10.2 | 8.9 | 4.8 | 5.8 | 6.8 | 6.3 | 10.1 | 0.1 | 10.2 | 16.3 | 3.8 |
| HCO₃⁻       | 692.0 | 490.0 | 379.0 | 100.8 | 118.5 | 98.2 | 103.1 | 102.7 | 72.4 | 148.2 | 91.7 | 85.4 | 354.9 | 167.6 |
| Sr         | 0.440 | 0.290 | 0.370 | 0.028 | 0.048 | 0.002 | 0.025 | 0.026 | 0.026 | 0.590 | 0.048 | 0.031 | 0.172 | 0.02305 |
| SiO₂       | 62 | 78 | 66 | 70 | 76 | 57 | 63 | 51 | 78 | 62 | 62 | 82 | 50 |
| Li         | 0.170 | 0.020 | 0.001 | 0.022 | 0.090 | 0.014 | 0.008 | 0.010 | 0.049 | 0.210 | 0.050 | 0.199 | 0.006 | 0.0076 |
| As         | 0.005 | 0.002 | 0.001 | 0.002 | 0.002 | 0.002 | 0.003 | 0.001 | 0.001 | 0.003 | 0.001 | 0.001 | 0.002 | 0.003 |
| F          | 1.6 | 1.7 | 0.3 | 2.5 | 6.8 | 3.4 | 6.5 | 1.4 | 1.8 | 3.0 | 5.8 | 0.8 | 2.2 | 0.3 |
| Hydrochemical type | HCO₃⁻-Na | HCO₃⁻-Na | HCO₃⁻-Na | HCO₃⁻-Na | HCO₃⁻-Na | HCO₃⁻-Na | HCO₃⁻-Na | HCO₃⁻-Na | HCO₃⁻-Na | HCO₃⁻-Na | HCO₃⁻-Na | HCO₃⁻-Na | HCO₃⁻-Na | HCO₃⁻-Ca-Na |
| Charge balance (%) | 6.0 | 3.0 | 3.9 | -0.3 | 6.2 | -6.2 | 3.5 | -8.1 | 0.0 | -1.8 | 1.8 | 6.0 | 7.0 | -3.5 | -0.5 |
| δD         | -72.6 | -67.2 | -63.3 | -78.9 | -72.1 | -69.6 | -70.9 | -74.0 | -72.9 | -71.5 | -70.9 | -68.2 | -70.6 | -57.8 | -69.1 |
| δ¹⁸O       | -10.9 | -9.6 | -9.2 | -11.1 | -10.8 | -10.6 | -10.7 | -11.1 | -10.9 | -9.9 | -10.7 | -10.0 | -10.3 | -9.6 | -9.18 |
| Elevation difference | 1631 | 1423 | 1273 | 1873 | 1612 | 1515 | 1565 | 1685 | 1642 | 1588 | 1565 | 1462 | 1554 | 1062 | 1015.384615 |
| Recharge elevation | 2831 | 2623 | 2543 | 3653 | 3119 | 3185 | 3255 | 3505 | 3362 | 2923 | 2715 | 2852 | 2794 | 2362 | 2215 |

Note: GS, geothermal spring; CS, cold spring; cations, anions, SiO₂, and TDS, trace elements in mg/L; isotopic ratio in ‰ relative to the VSMOW standard; elevation in m.
of rock-forming. For this reason, the relationship between the Cl and other major ions is efficient to trace the hydro-geochemical processes during the formation of geothermal waters. In this study, the relationship between the Cl content and other ion concentrations is shown in Figure 4. It is noteworthy that Cl contents had an obvious linear relationship with K (squared regression coefficient = 0.9336), Na (squared regression coefficient = 0.8362), and SiO$_2$ (squared regression coefficient = 0.7019). Low-temperature geothermal waters in the Mangbang-Longling area were believed to be the results by mixture between surface cold water and a deep geothermal fluid. Notably, the squared regression coefficient of K vs. Cl was higher than squared regression coefficients of Na vs. Cl and SiO$_2$ vs. Cl. Considering widespread exposure of silicate rocks (granitic and metamorphic rocks) in the Mangbang-Longling area, the concentrations of Na and SiO$_2$ were probably influenced by water-rock reaction (dissolution of silicates) and ion exchange.

However, the plots in the Ca, Mg, HCO$_3$, SO$_4$, and F vs. Cl diagrams represented scattered distributions, suggesting
that these ions are derived from multiple sources (Figures 4(e)–4(i)). Ca, Mg, and HCO$_3$ were originated from the dissolution of calcite and dolomite, in the case of the Ca/HCO$_3$ and (Ca+Mg)/HCO$_3$ ratios of 1. In this study, the Ca/HCO$_3$ and (Ca+Mg)/HCO$_3$ ratios were lower than 1 (Figures 5(a) and 5(b)). Meanwhile, the saturation indices of carbonate minerals (calcite and dolomite) were lower than zero, excluding the possibility of carbonate reservoir. The depletion of Ca and Mg were attributed to ion exchange from silicates dissolution, while enrichment of HCO$_3$ in the silicate reservoir was probably derived from escaped geothermal gases dominated by CO$_2$. The concentrations of Ca and SO$_4$ did not yield a 1:1 line in Figure 5(c), implying hydrogeochemical concentrations of geothermal waters is unlikely determined by dissolution of gypsum. Large number of the samples were plotted along the 1:1 line in the (Na + K)–Cl and (Ca + Mg)–(SO$_4$ + HCO$_3$) diagram. Hence, the hydrogeochemical composition of the
samples was mainly attributed to a cation-exchange process which is the result of silicate dissolution (Figure 5(d)).

5.2. Reservoir Temperature and Circulation Depth. Geothermometers determining reservoir temperature are based on the equilibrium of temperature-dependent reactions that occur in the reservoir [36].

5.2.1. Classical Geothermometry. The classical chemical geothermometers (e.g., cation and silica) are applicable for the estimation of the equilibrium temperature in geothermal reservoirs [37–39]. Considering this, cation and silica geothermometers were used to calculate the equilibrium temperatures, whose results are listed in Table 3. However, the results from the cation geothermometers had a great range and variation with wellhead temperatures. In the Na-K-Mg ternary diagram, all plots of geothermal waters were largely deviated from the full equilibrium line and plot in the area of immature waters (Figure 6). Saturation indices of most minerals (except quartz and chalcedony) lower than zero were also typical of immature affinity. Hence, none of the low-temperature geothermal waters in the Mangbang-Longling area had reached full equilibrium with the host rock. In this study, silica geothermometers were more applicable to the geothermal waters than cation geothermometers in this study. Additionally, the oversaturated condition of silicate minerals (quartz and chalcedony) also supported the feasibility of silica geothermometers.

Silica geothermometry, including quartz and chalcedony geothermometers, is the approach to estimate reservoir temperature considering the soluble concentrations of silica minerals. Various silica geothermometers...
were applied in this study (Table 3). Of note, the chalcedony geothermometer was chosen on the basis of the distribution of samples in the log(K2/Mg) versus the log(SiO2) diagram (Figure 7).

Quartz geothermometer is applied for the reservoir with high temperatures at 150°C and above, while chalcedony geothermometer yields more accurate results when geothermal waters reach equilibrium below 180°C [45]. In the Mangbang-Longling area, the estimated reservoir temperatures calculated by silicagethermometers were lower than 150°C. As such, it is believable that the estimate reservoir temperatures of geothermal waters in the Mangbang-Longling area ranged 111–126°C calculated by the chalcedony geothermometer.

5.2.2. Silicon-Enthalpy Graphic Method. Cold water is believed to be involved in the formation of low-temperature geothermal water due to the immature affinity. In this study, the silica-enthalpy mixing model with the plots of cold and geothermal water was used to estimate the reservoir temperature and mixing ratio (Figure 8) [39]. In the silica-enthalpy mixing model, the average value of cold water samples was chosen as end member point “a” and geothermal water samples were noted as end member point “b.” A red line linking end member points “a” and “b” intersected with the vertical line of the boiling point (96°C) at point “c” and Quartz solubility line at the point “d.” The horizontal axis of point “d” (151°C) suggested the reservoir temperature when no steam separated before

| Sample no.       | GS1 | GS2 | GS3 | GS4 | GS5 | GS6 | GS7 | GS8 | GS9 | GS10 | GS11 | GS12 | GS13 | GS14 |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|------|------|
| Quartz [40]      | 144 | 151 | 146 | 148 | 151 | 141 | 144 | 137 | 142 | 151  | 144  | 144  | 153  | 137  |
| Quartz (maximum steam loss) [40] | 138 | 145 | 140 | 141 | 144 | 136 | 139 | 133 | 137 | 145  | 145  | 138  | 138  | 146  |
| Chalcedony [41]  | 118 | 126 | 122 | 125 | 115 | 118 | 111 | 116 | 126 | 118  | 118  | 128  | 111  |
| Na-K [38]        | 191 | 203 | 213 | 117 | 110 | 139 | 101 | 126 | 142 | 143  | 168  | 146  | 211  | 197  |
| Na-K-Ca [36]     | 152 | 153 | 148 | 100 | 96  | 106 | 88  | 104 | 111 | 127  | 132  | 117  | 190  | 131  |
| K-Mg [38]        | 58  | 58  | 45  | 83  | 74  | 58  | 76  | 83  | 58  | 105  | 67   | 68   | 175  | 45   |

Figure 6: Graphical evaluation of water-rock equilibration temperatures for geothermal waters using Na-K-Mg concentrations in “mg/L” [38].

Figure 7: Cross-plot of log(K2/Mg) vs. log(SiO2), unit: mg/L [42]. The lines are drawn using log(SiO2) = 4.52 – (731/(t°C + 273.15)) for amorphous silica, log(SiO2) = 4.69 – (1032/(t°C + 273.15)) for chalcedony, and log(SiO2) = 5.19 – (1309/(t°C + 273.15)) for quartz from [43] and log(K2/Mg) = 14 – (4410/(t°C + 273.15)) from [44].
mixing. Point “c” was intersected horizontally with the maximum steam loss line at point “e.” The horizontal axis of point “e” (123°C) was the reservoir temperature in the condition of steam separation occurs before mixing. Therefore, the reservoir temperature of 123°C obtained by point “e” was more comparable to the results calculated by the chalcedony geothermometer (111–126°C). The mixing ratio of shallow cold water can be approximately obtained by the length ratio between line ab and line ad, that is to say, 72%.

Fournier [46] raised the silica-enthalpy equations to estimate the mixing ratios of cold waters and the temperatures of initial geothermal waters. The silica-enthalpy equations are given as follows:

\[
H_cX + H_b(1 - X) = H_s, 
\]

\[
Si_cX + Si_b(1 - X) = Si_s. 
\]

In equations (1) and (2), \(H_b\) is the enthalpy of initial geothermal water, \(H_c\) signifies the enthalpy of cold water, \(H_s\) represents the enthalpy of geothermal water, \(X\) is the mixing ratio of cold water, \(Si_b\) defines the SiO2 contents of initial geothermal water, and \(Si_c\) shows the SiO2 contents of cold water. The results of silica-enthalpy equations indicated the mixing ratios of cold waters, and the temperatures of initial geothermal waters are 69–74% and 180–270°C.

5.2.3. Circulation Depth. When geothermal water is heated by heat flow from below, the circulation depth of geothermal water in the studied area is estimated using the following equation:

\[
Z = \frac{(T_Z - T_0)}{G} + Z_0, 
\]

where \(Z\) is the circulation depth (m), \(T_Z\) is the geothermal reservoir temperature obtained by a reasonable thermometer (°C), \(T_0\) is the annual average temperature of recharge area (°C), \(G\) is thermal gradient (°C/m), and \(Z_0\) is the thickness of the constant temperature zone (m). In this study case, the annual average temperature of recharge area is 17.5°C, and therefore, \(T_0 = 17.5°C\), \(Z_0 = 30\) m, and \(G = 5.3°C/100\) m [47, 48]. Based on the above calculated reservoir temperatures (111–126°C), the largest circulation depth of geothermal water was inferred as 1794–2077 m in the Mangbang-Longling area.

5.3. Recharge Origin. H and O stable isotopes (\(\delta D\) and \(\delta^{18}O\)) have been proved to be a robust way for tracing recharge origin of geothermal water. In this study, the geothermal waters present the \(\delta D\) values of −57.8‰ to −78.9‰ (average = −70.0‰) and \(\delta^{18}O\) values of −9.2‰ to −11.1‰ (average = −10.4‰), respectively. The plots of geothermal waters were close around the local meteoric water line (LMWL) in the \(\delta D–\delta^{18}O\) graph (Figure 9), indicative of a meteoric origin. Geothermal water plots were slightly deviated from the LMWL and further link with high-temperature geothermal water and magmatic water in a straight line. Hence, weak water-rock interaction and involvements of high-temperature geothermal water occurred in the formation of low-temperature geothermal water.

\(\delta D\) and \(\delta^{18}O\) values have been extensively employed to calculate the recharge elevation because of their altitude effect. Considering the existence of oxygen drifting, the \(\delta D\) values of the geothermal waters are more reliable to estimate the recharge elevation in this study. The recharge elevation difference (\(\Delta H\)) of geothermal water are calculated based on the following equation: \(\delta D = -0.026\Delta H - 30.2\) [49, 50]. Accordingly, the recharge elevation differences of the low-temperature geothermal waters in the Mangbang-Longling area were calculated as 1062–1873 m, indicating the elevations of recharge area range from 2362 m to 3653 m. The recharge elevation well coincided with the elevation range of 900–3800 m in the study area.

5.4. Conceptual Model of Low-Temperature Geothermal Waters in the Mangbang-Longling Area. According to the geological condition and hydrogeochemical and isotopic results above, a conceptual model of low-temperature geothermal water in the Mangbang-Longling area was built as schematically depicted in Figure 10, which is a qualitative, schematic representation of (or part of) reality. Geothermal water was recharged by common meteoric water at the elevation of 2362–3653 m. Afterward, meteoric water is driven by topographical conditions, flows along fault and fractures, and finally transfers to geothermal water by heating by heat flow from below. Assuming a geothermal gradient of 5.3°C/100 m, geothermal water infiltrates into the subsurface at the reservoir with the largest circulation depth of 1794–2077 m and temperature of 111–126°C. During the circulation, the hydrogeochemical characteristics of geothermal water (HCO3-Na type) were mainly determined by the water-rock interaction with a widespread silicate aquifer.
It is noteworthy that the involvement of high-temperature geothermal water had been verified during the formation of low-temperature geothermal water. Finally, low-temperature geothermal water was mixed with up to 72% shallow cold water of HCO₃-Ca type and exposed as geothermal spring in the high permeability areas, such as fault and fracture intersection.

Figure 9: Plots of $\delta^{18}$O vs. $\delta$D for the geothermal water and cold water samples, modified after [17]. GMWL, global meteoric water line; LMWL, local meteoric water line. Low-temperature geothermal water and cold water samples are from this study. High-temperature geothermal water samples are cited from [17].

Figure 10: Conceptual model of low-temperature geothermal water in the Mangbang-Longling area.
6. Conclusion

This study was the first to present the hydrogeochemistry and geothermometry of the low-temperature thermal waters in the Mangbang-Longling area of western Yunnan. In this context, the results obtained from geochemical and isotopic studies are listed as follows.

1. The low-temperature geothermal waters were characterized by HCO$_3$-Na type, while shallow cold spring is of the hydrochemical type of HCO$_3$-Ca

2. Hydrogeochemical characteristics of low-temperature geothermal waters were mainly affected by the water-rock interaction with silicate minerals

3. Low-temperature geothermal waters possessed reservoir temperature of 111–126°C and largest circulation depth of 1794–2077 m and were mixed with up to 72% shallow cold waters

4. $\delta$D and $\delta^{18}$O evidence showed the low-temperature thermal waters were recharged by meteoric water at the elevation of 2362 m to 3653 m. The data points of $\delta$D and $\delta^{18}$O of the hot spring water samples in the study area show a linear right-up trend, indicating the $\delta^{18}$O reaction between the water and rock and a possible mixture of magmatic water from below. Deep high-temperature geothermal waters were involved in the formation of low-temperature thermal waters.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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