Hydrogeochemistry of Hot Springs and the 2018 Mojiang M 5.9 Earthquake-Related Chemical Changes in the Simao Basin, China

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Hydrogeochemistry of hot springs and the 2018 Mojiang M 5.9 earthquake-related chemical changes in the Simao Basin, China

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Abstract

Due to strong tectonic activity, the Simao Basin frequently experiences earthquakes with a magnitude of 6 or greater. This study investigated the hydrochemical characteristics of 21 thermal springs in the Simao Basin from 2018 to 2020 to determine how the 2018 Mojiang M5.9 earthquake caused hydrochemical changes. The results showed that the Simao Basin contained saline spring waters, HCO_3^- -rich spring waters, and SO_4^{2-} -rich spring waters. Stratum lithology characteristics in the area exerted obvious control over the water chemistry characteristics. Saline springs flowed through red beds and dissolved large amounts of halite, which is rich with Cl^- and Na^+ . Ca^{2+} (Mg^{2+}) and HCO_3^- in the hot spring waters were mainly derived from the dissolution of carbonate minerals, gypsum, and anhydrite in Triassic rocks. The higher SO_4^{2-} content in the hot spring waters was influenced by pyrite contained in Ailaoshan metamorphic rocks. The reservoir temperatures (121–289° C) in the Simao Basin were estimated by the silica-enthalpy mixing model equation and silica-enthalpy diagram. The hot springs with higher reservoir temperatures (> 250° C) were mainly located at the edges of the basin, which may correlate with nearby deep faults that provided deep heat and metamorphic rocks with low permeabilities. The concentrations of Ca^{2+} and HCO_3^- in most springs increased obviously before the Mojiang M5.9 earthquake but decreased after the earthquake. Changes also occurred in the reservoir temperatures of some spring samples. These hydrogeochemical variations might be attributable to accelerated water-rock interactions and/or the mixing of second fluids due to the earthquake.

Keywords: hot spring, earthquake, hydrochemical characteristics, reservoir temperature, chemical changes

Introduction

The Simao Basin (the southern half of the Lanping-Simao Basin) located in the Yunnan-Tibet geothermal belt is a typical red-bed Basin with strong tectonic activity (Figs. 1a and b). Various types and quantities of springs exist in the basin. The hydrochemical characteristics of hot springs help reveal information about geothermal reservoirs and thermal groundwater circulation and may provide insight into potential geothermal resources and the subsurface transport of substances. Some studies on springs in the Simao Basin have focused on potassium exploration through salty and saline

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30 springs, the exploration and utilization of geothermal resources, and the origin and evolution of the springs were also
 31 examined [1-4]. However few reports have studied the earthquake-related composition of groundwater characteristics and
 32 changes in the basin. The study area is located in the Simao-Pu'er seismic zone, which is one of the most important strong
 33 earthquake disaster areas in the Yunnan province [5]. It is helpful to study the hydrochemical characteristics and changes
 34 in the hot springs in order to understand the breeding process of strong earthquakes in this district.

35 Earthquake-related groundwater chemical composition changes have been widely used in the search for seismic
 36 precursors. Tsunogai et al. [6] observed increased Cl^- and SO_4^{2-} concentrations in groundwater prior to the Kobe earthquake
 37 in Japan. Claesson et al. [7] observed a rapid increase in multicomponent constituents and a decrease in the Na/Ca content
 38 of groundwater due to a seismic event ($M = 5.8$) in northern Iceland. Changes in the concentrations of Ca^{2+} and HCO_3^-
 39 were observed before and after the Wenchuan earthquake ($M_s = 8.0$), the Lushan earthquake ($M_s = 7.0$), and the Kangding
 40 earthquake ($M_s = 6.3$) in China [8, 9]. Seismic hydrochemical changes may be linked to changes in the permeability
 41 structure, the mixture of deep and shallow fluids, and/or fluid-rock interactions caused by tectonic activity [10, 11].

42 Here, new hydrochemical data from hot springs in the Simao Basin are reported. We investigated the hydrochemical
 43 characteristics of these thermal springs from 2018 to 2020. During the study period, the 2018 Mojiang $M_{5.9}$ earthquake
 44 occurred in the study area and caused significant hydrochemical changes. Earthquake-related hydrochemical changes were
 45 studied and the possible mechanisms in the geothermal area were explained.

46
 47 **Fig. 1.** Topographic map of the study area (a) and schematic tectonics and spring sites in the Simao Basin (b; modified
 48 from Zhang et al.) [12]. Abbreviations: F1 = Lancangjiang fault, F2 = Wuliangshan fault, F3 = Ailaoshan fault, F4 = Mohei
 49 fault.

Geological setting

The Simao basin is located in southwest Yunnan, China and belongs to the southern section of the Sanjiang fold system, which is narrow in the north and wide in the south in the shape of a broom (Figs. 1a and b) [13]. Several huge NW–SE and nearly S–N trending faults control the formation and tectonic evolution of the basin. The Lancangjiang deep fault (F1) in a roughly S–N direction and the Ailaoshan deep fault (F3) in a NW–SE direction are the western and eastern margins of the basin, respectively. A series of NW–SE trending faults have developed in the basin—for instance, the Wuliangshan fault (F2) and the Mohei fault (F4) (Fig. 1) [14]. Most parts of the Simao Basin are underlain by thick Mesozoic and Cenozoic red beds. Proterozoic metamorphic rocks are only exposed in the margin of the basin. The Upper and Middle Paleozoic limestones outcrop in the central block uplifts and the marginal belt uplifts in the basin [15]. According to seismic records, many moderate to strong crustal earthquakes have occurred in the basin, including the 2007 Ning'er earthquake (Ms 6.4), the 2014 Jinggu earthquake (Ms 6.6, Ms 5.8, and Ms 5.9), and the 2018 Mojiang earthquake (Ms 5.9) (<http://www.ceic.ac.cn/>). The Simao Basin is situated in the southern Yunnan-Tibet geothermal zone, which shows strong geothermal activity. The active crustal movement creates favorable conditions for the formation of high-temperature geothermal fields [16] with a terrestrial heat flow of 63.2 MW/m² [17]. The distribution of the banded geothermal wells are controlled by the tectonic activities that formed deeper fracture zones, which can provide channels for the enrichment and migration of geothermal fluids.

Materials and methods

Hot springs were geochemically investigated in the Simao basin from 2018 to 2020, and 38 hydrothermal water samples were obtained (sampling locations shown in Fig. 1b). Based on previous studies, we collected more hydrochemical data from these thermal spring samples in the 1980s and in 2017. The sampling locations and information are listed in Table 1. The field investigations include on-site measurements of pH, temperature, electrical conductivity (EC), which were measured with a portable multi-parameter water quality analyzer (produced by WTW, Germany). The precision of these factors were 0.01, 0.1 °C, and 1 μS·cm⁻¹, respectively. During sampling, the water samples for analysis were filtered through a 0.45-μm membrane filter and then stored in plastic bottles. All samples were measured at the deep-earth fluids laboratory, Yunnan Earthquake Administration, China. Cations (Na⁺, K⁺, Ca²⁺, Mg²⁺, Li⁺, NH₄⁺, Rb⁺, Cs⁺, Sr²⁺) and anions (F⁻, Cl⁻, NO₂⁻, Br⁻, NO₃⁻, SO₄²⁻) were tested by ion chromatography (883 Basic IC plus, Metrohm, Switzerland; detection limit: 0.01 mg·L⁻¹). SiO₂ (aq), HCO₃⁻, and CO₃²⁻ were detected according to the China National Standard Examination Methods for Drinking Natural Mineral Water (GB/T 8538-2008). SiO₂ (aq) was measured by a visible spectrophotometer, and HCO₃⁻ and CO₃²⁻ by the volumetric method (HCl titration).

80 Results

81 Hydrogeochemistry and earthquake-induced chemical variations

82 **Fig. 2.** Piper diagram (a) and Schoeller diagram (b) of the geothermal waters. Process (black circles) indicating the
83 changes before and after the Mojiang earthquake.
84

85
86 The physicochemical parameters and geochemical data of hot springs in the Simao basin are listed in Table 1 and
87 Table 2. The 21 hot springs had temperatures ranging between 30 °C and 102 °C. The pH values and total dissolved solids
88 (TDS) were 5.60–8.26 and 237–10444 mg/L, respectively. The saline spring samples (No. 3, 4, and 5) had relatively higher
89 TDS values (5351–10444 mg/L) than others. Based on the data for ions (K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , and HCO_3^-) in
90 the thermal springs from the 1980s to 2020, the Piper and Schoeller diagrams (Figs. 2) show the concentrations of major
91 and minor ions in springs. In the Piper diagram, the 21 water samples are roughly divided into three groups. Saline spring
92 waters are of Na–Cl type. Samples containing HCO_3^- as the predominant anion ($HCO_3^- > SO_4^{2-} > Cl^-$ or $HCO_3^- > Cl^- >$
93 SO_4^{2-}) include Na- HCO_3 , Ca- HCO_3 , Ca-Na- HCO_3 , Na-Ca- HCO_3 , Na- HCO_3 - SO_4 , Na- HCO_3 -Cl, Na-Ca- HCO_3 - SO_4 , and
94 Na- HCO_3 -Cl- SO_4 . Samples containing SO_4^{2-} as the predominant anion ($SO_4^{2-} > HCO_3^- > Cl^-$ or $SO_4^{2-} > Cl^- > HCO_3^-$)
95 include Ca- SO_4 , Na-Ca- SO_4 , Ca-Na- SO_4 , Na- SO_4 - HCO_3 , and Na-Ca- SO_4 - HCO_3 . Other ions (Li^+ , NH_4^+ , Rb^+ , Cs^+ , Sr^{2+} , F^- ,
96 NO_2^- , Br^- , NO_3^-) were present in relatively low concentrations. The components F^- , and Sr^{2+} of data points 14–21 had
97 relatively higher concentrations, which may suggest that these spring waters undergo deep circulation.

98 Fig. 3 shows the relationships between major ions of the spring water, i.e. HCO_3^- vs. Na^+ , Na^+ vs. Cl^- , SO_4^{2-} vs. Ca^{2+} ,
99 HCO_3^{2-} vs. Ca^{2+} , $(Ca^{2+} + Mg^{2+})$ vs. $(HCO_3^- + SO_4^{2-})$ and SO_4^{2-} vs. Cl^- . Except for data points 3, 4, 5, 8, 9, and 12, the
100 majority of data points plot close to the 1:1 line in Figure 3(a), indicating that the quality of Na is influenced by the

101 dissolution of Na-feldspar. Samples 8 and 9 fall to the lower-right of the 1:1 line, which means that HCO_3^- has another
 102 source. Fig. 3d illustrates that carbonate minerals (calcite and dolomite) are also a source of HCO_3^- . The values of HCO_3^-
 103 and Na^+ in saline spring waters of 3, 4, 5, and 12 are much greater than 1, suggesting that the dissolution of Na-feldspar is
 104 not the main source of these ions (Fig. 3a). Spring samples 3, 4, and 5 are located in Jinggu County, which has large halite
 105 deposits [13]. In Figure 3(b), saline spring samples of 3, 4, 5, and 12 with high Cl^- and Na^+ contents lie on the dissolution
 106 line of NaCl, showing that halite is the main source of Na. Except for data points 6, 7, 8, and 9 in the Triassic carbonate
 107 rocks, most water falls near the 1:1 line (gypsum dissolution line), suggesting that the dissolution of gypsum and anhydrite
 108 is the main source of Ca^{2+} and SO_4^{2-} (Fig. 3c). Data points of 6, 7, 8, and 9 fall above the trend lines of SO_4^{2-} and Ca^{2+} ,
 109 demonstrating that there is another source of Ca^{2+} apart from gypsum and anhydrite. The Triassic carbonate strata in the
 110 Simao Basin are located under the Jurassic red bed. The spring water flows through carbonate formations and can dissolve
 111 calcite and dolomite. Anhydrite is distributed in the thin interlayer of the salt series, and gypsum is distributed in the mud
 112 conglomerate layer on the surface [14]. The ionic ratios of $(\text{Ca}^{2+} + \text{Mg}^{2+})$ vs. $(\text{HCO}_3^- + \text{SO}_4^{2-})$ in Figure 3e show that the
 113 dissolution of dolomite, calcite, gypsum, and anhydrite is responsible for the production of Ca^{2+} , Mg^{2+} , SO_4^{2-} , and HCO_3^- .
 114 A correlation between Cl^- and SO_4^{2-} can be inferred from Fig. 3f. The positive chloride-sulfate relation probably reflects
 115 the mixing of geothermal water and cold water. Atmospheric oxygen in the cold water oxidizes H_2S to SO_4^{2-} at shallow
 116 depths, which increases the SO_4^{2-} concentration of the geothermal water, (e.g., sampling points 10, 11, 18, 19, 20, and 21).
 117 In addition, the lithology suggests that the dissolution of the pyrite-bearing formation rocks near the Ailaoshan fault may
 118 increase the SO_4^{2-} content in the groundwater [18].

Fig. 3. Relationship plots of major ions of the spring water in the Simao Basin.

The waters in different springs have the same chemical characteristics, which indicates they may be derived from the same source. As shown in the Piper diagram (Fig. 2), the water chemistry in No.7 and 13 changed during the study period. No.7 is located in the near-field of the Mojiang earthquake. The water chemistry in No.7 changed from Na-HCO₃-Cl to Na-Ca-HCO₃ in June 2018 before the Mojiang M5.9 earthquake on September 8 and from Na-Ca-HCO₃ back to Na-HCO₃-Cl in 2020. Similarly, the water chemistry in No.13 changed from Na-Ca-Cl-SO₄-HCO₃ to Na-Ca-HCO₃-Cl-SO₄ before the Mojiang M5.9 earthquake and from Na-Ca-HCO₃-Cl-SO₄ back to Na-Ca-Cl-SO₄-HCO₃ after the earthquake; however, no significant changes were found in other spring samples (Table 2). The time series of anion and cation ions for these springs were plotted. Ca²⁺ and HCO₃⁻ ions in the springs exhibited significant changes before the Mojiang M5.9 earthquake, while other ions stayed relatively stable. We found that the concentrations of Ca²⁺ and HCO₃⁻ in most springs (blue lines) increased obviously before the Mojiang M5.9 earthquake but decreased after the earthquake (Fig. 4). Data points 1, 2, 6, 8, 9, 18, 19, 20, and 21 (black lines) changed slightly before and after the earthquake. The Na/Ca ratio appears to be

136 sensitive to the changing stresses associated with $M > 4$ earthquakes [7]. In Fig. 4, the Na/Ca data decreased before the
 137 Mojiang M5.9 earthquake. After the earthquake, the Na/Ca ratio increased slightly and then recovered in 2020.

138
 139 **Fig. 4.** Hydrogeochemical changes of the thermal springs from the 1980s to 2020.

140

141 **Table 1**

142 Location, physicochemical parameters, and water type of the thermal springs in the Simao Basin.

Sample No.	Site Name	Long. (E°)	Lat. (N°)	Time	<i>T</i>	pH	EC	TDS	Water Type ^a
1a	Zhongcang hot spring	100.609226	24.681837	1982/12	43.5	7.00	—	1344	Na-HCO3-SO4
1b				2018/6	47.5	6.37	2400	2090	Na-HCO3-SO4
1c				2019/3	31.2	6.68	2030	1741	Na-Ca-HCO3-SO4
1d				2020/6	30.1	6.69	2300	1664	Na-HCO3-SO4
2a	Xiejitian hot spring	100.458191	23.915453	1982/12	51.5	7.00	—	1399	Na-Cl-SO4
2b				2018/6	49.8	6.74	2290	1574	Na-HCO3-Cl

2c				2019/3	49.8	6.83	2280	1554	Na-HCO3-Cl-SO4
2d				2020/6	50.8	6.89	2560	1564	Na-Cl-HCO3-SO4
3b				2018/6	38.0	6.75	10000	5681	Na-Cl
3c	Mangfei spring	100.645755	23.420093	2019/3	36.6	6.90	10470	5418	Na-Cl
3d				2020/6	34.7	6.75	11230	6001	Na-Cl
4a				1982/12	49.5	6.70	—	6076	Na-Cl
4b	Huanle hot spring	100.698025	23.41941	2018/6	53.5	6.18	9880	5739	Na-Cl
4c				2019/3	43.0	6.96	8120	5351	Na-Cl
4d				2020/6	50.1	6.24	11290	5460	Na-Cl
5a				1982/12	56.5	6.50	—	10444	Na-Cl
5b	Yanshuihe hot spring	100.742147	23.594417	2018/6	57.0	6.70	16150	9132	Na-Cl
5c				2019/3	57.5	7.64	16350	8671	Na-Cl
5d				2020/6	56.7	6.59	17600	8918	Na-Cl
6a				1981/12	48.6	7.00	—	407	Ca-Na-HCO3
6b	Xisa hot spring	101.001243	23.211148	2018/6	48.4	6.82	665	557	Ca-Na-HCO3
6c				2019/3	47.8	7.03	666	528	Ca-Na-HCO3
6d				2020/6	48.1	6.86	747	422	Ca-Na-HCO3
7a				1984/5	62.5	7.00	—	952	Na-HCO3-Cl
7aa				2017/8	65.8	5.80	—	1436	Na-HCO3-Cl
7b	Qingping hot spring	101.432	23.320927	2018/6	64.5	6.80	1762	1532	Na-Ca-HCO3
7c				2019/3	67.0	7.80	1743	1397	Na-Ca-HCO3
7d				2020/6	62.9	7.68	1926	1167	Na-HCO3-Cl
8a				1981/12	32.8	6.70	—	278	Ca-HCO3
8b	Hualiang spring	101.00443	23.043033	2018/6	32.3	7.03	503	473	Ca-HCO3
8c				2019/3	32.2	7.14	497	444	Ca-HCO3
8d				2020/6	32.3	7.05	532	373	Ca-HCO3
9a				1984/4	30.0	6.50	—	237	Ca-HCO3
9b	Sanjiacun spring	100.742983	22.754458	2018/6	30.3	6.80	589	521	Ca-HCO3
9c				2019/3	29.9	7.07	591	536	Ca-HCO3
9d				2020/6	30.0	7.07	616	319	Ca-HCO3
10a				1984/4	53.5	6.70	—	1977	Na-Ca-SO4-HCO3
10b	Dashujiao hot spring	101.274907	22.810465	2018/6	51.0	6.64	3220	2785	Na-Ca-SO4-HCO3
10c				2019/3	51.0	7.20	3290	2562	Na-Ca-SO4-HCO3
10d				2020/6	41.9	6.54	3680	2674	Na-Ca-SO4-HCO3
11a				1984/4	40.5	6.70	—	1334	Na-Ca-SO4-HCO3
11b	Landuifang spring	101.304428	22.794271	2018/6	39.8	6.46	1858	1438	Na-Ca-HCO3-SO4
11c				2019/3	39.9	6.73	1979	1434	Na-Ca-HCO3-SO4
11d				2020/6	39.3	6.52	1915	1240	Na-Ca-SO4-HCO4
12a				1984/4	50.5	7.00	—	2522	Na-Cl
12aa				2017/7	40.6	5.70	—	3209	Na-Cl-HCO3
12b	Manzhongtian hot spring	101.343186	22.676214	2018/6	55.0	6.48	5080	3230	Na-Cl-HCO3
12c				2019/3	54.1	6.41	5090	2981	Na-Cl-HCO3
12d				2020/6	49.7	6.37	5600	3187	Na-Cl-HCO3
13a	Zhongdong spring	101.532875	22.508095	1984/4	41.0	6.40	—	1621	Na-Ca-Cl-SO4-HCO3

13aa				2017/7	40.8	5.60	—	1813	Na-Ca-Cl-SO ₄ -HCO ₃
13b				2018/6	35.0	6.84	2500	1770	Na-Ca-HCO ₃ -Cl-SO ₄
13c				2019/3	35.0	6.94	2090	1715	Na-Ca-HCO ₃ -Cl-SO ₄
13d				2020/6	35.9	6.90	2850	1612	Na-Ca-Cl-SO ₄ -HCO ₃
14a				1983/12	43.5	7.00	—	928	Na-HCO ₃
14c	Pingkun spring	102.463591	22.8542	2019/3	40.3	7.26	1397	1321	Na-HCO ₃
14d				2020/6	42.0	7.33	1549	1273	Na-HCO ₃
15c	Baha hot spring	102.626560	22.796782	2019/3	72.0	8.00	810	694	Na-HCO ₃
15d				2020/6	72.1	8.18	914	666	Na-HCO ₃
16a				1983/12	59.0	7.20	—	423	Na-HCO ₃
16c	Puer hot spring	103.0441	22.653311	2019/3	51.8	7.30	482	427	Na-HCO ₃
16d				2020/6	51.8	7.25	553	391	Na-HCO ₃
17c	Nanxing hot spring	103.028505	22.533045	2019/3	65.0	7.99	962	870	Na-HCO ₃
17d				2020/6	64.8	7.31	1123	754	Na-HCO ₃
18a				1983/12	51.0	7.00	—	1074	Na-Ca-SO ₄
18b	Dadipeng hot spring	103.361475	22.990371	2018/6	50.8	6.97	1270	914	Ca-Na-SO ₄
18c				2019/3	48.1	7.44	1284	853	Ca-Na-SO ₄
18d				2020/6	50.8	7.00	1429	943	Ca-Na-SO ₄
19b				2018/6	40.0	6.82	2450	2163	Ca-SO ₄
19c	Mapiyi spring	103.45726	22.902029	2019/3	40.5	6.97	2480	1953	Ca-SO ₄
19d				2020/6	40.6	6.99	2750	2246	Ca-SO ₄
20b				2018/6	77.0	7.48	1162	823	Na-Ca-SO ₄ -HCO ₃
20c	Malizhai hot spring	103.4285	22.931684	2019/3	76.0	7.26	1280	788	Na-Ca-SO ₄ -HCO ₃
20d				2020/6	75.1	6.88	1375	782	Na-Ca-SO ₄ -HCO ₃
21a				1983/12	102.2	7.50	—	915	Na-SO ₄ -HCO ₃
21b	Mengping hot spring	103.488815	22.913696	2018/6	94.0	8.26	1137	791	Na-SO ₄ -HCO ₃
21c				2019/3	93.0	7.90	1189	701	Na-SO ₄ -HCO ₃
21d				2020/6	91.2	7.79	1270	799	Na-SO ₄ -HCO ₃

144 **Table 2**
145 Chemical composition of the hot spring waters in the Simao Basin.

Sample No.	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Li ⁺	NH ₄ ⁺	Rb ⁺	Cs ⁺	Sr ²⁺	F ⁻	Cl ⁻	NO ₂ ⁻	Br ⁻	NO ₃ ⁻	CO ₃ ²⁻	HCO ₃ ⁻	SO ₄ ²⁻	SiO ₂
1a	459.00	25.60	7.01	18.20	0.38	0.28	0.110	0.410		1.67	121.00				19	723	280.00	39
1b	465.79	13.34	100.78	16.94	0.55		0.032	0.300	1.98	1.84	93.97			0.023		1131	263.31	40
1c	361.01	13.16	89.40	14.05	0.42				1.50	1.33	76.24	0.013	0.009	3.885		961	219.49	29
1d	423.87	11.78	40.93	15.53	0.47				1.56	1.75	94.89	0.005	0.008	1.845		786	285.32	39
2a	440.00	18.10	55.50	8.90	0.84	0.88	0.050	0.150		1.85	347.00				13	311	281.00	67
2b	432.58	7.20	76.72	4.76	0.99		0.024	0.572	3.11	1.89	278.87			0.014		559	208.64	69
2c	411.39	9.09	71.94	4.54	0.93		0.004	0.578	3.00	1.76	260.19	0.238	0.062	0.062		549	241.04	60
2d	415.08	6.99	48.98	4.61	0.93				2.86	2.29	335.97			0.072		421	325.64	67
3b	2073.95	24.80	197.25	27.95	1.00				0.00	1.31	2749.55		0.062	1.054		390	214.36	34
3c	1949.40	20.12	127.26	15.05					3.65	1.51	2602.38		0.464	0.939		400	297.96	33
3d	1995.10	20.79	127.01	15.59					3.72	1.62	3180.67		0.556	3.425		281	371.56	31
4a	1995.00	34.10	195.00	37.30	0.45	1.02	0.140	0.360		1.85	3013.00					260	620.00	45
4b	1933.95	16.95	288.45	32.05	0.60	30.60			0.00	1.24	2421.00					647	367.67	48
4c	1794.69	13.02	189.55	17.30				0.718	4.05	1.14	2228.54		0.233	0.025		610	492.03	22
4d	1874.56	13.82	170.73	20.14					4.38	0.58	2614.85	1.665	0.195	0.565		189	569.35	43
5a	3590.00	56.10	375.00	44.10	1.06	1.74	0.240	0.390		2.32	5246.00					165	1000.00	39
5b	3146.30	27.70	473.30	41.30	1.30				7.00	0.68	4478.45			0.016		366	590.11	37
5c	3098.10	24.88	246.07	16.45					4.93	0.62	4105.40		0.765	0.041		354	820.10	35
5d	3097.25	24.91	255.11	17.86					5.61	0.71	4474.50	0.675	0.012	1.016		133	906.63	40
6a	56.70	2.55	72.30	11.00	0.04	0.34				0.50	55.90					292	27.00	33
6b	49.85	1.78	84.05	9.29	0.02				0.89	0.45	36.48			0.004		368	6.42	32
6c	47.93	1.71	79.62	8.56	0.03				0.75	0.50	34.53		0.002	0.006		348	6.45	20
6d	52.59	1.69	59.74	8.75	0.02				1.11	0.66	37.35		0.001	0.071		253	7.49	28
7a	282.00	24.90	16.60	23.50	0.64	5.20	0.520	0.470		1.12	169.00					595	70.00	56
7aa	259	19.6	60.7	14.2	0.47		0.071		1.75	0.32	144		0.18	0.04		891	47.90	47
7b	255.71	19.13	123.04	22.27	0.78		0.038	0.795	1.55	0.60	120.11					965	22.49	61
7c	143.07	20.16	115.59	11.24	0.74		0.023	0.730	1.48	0.49	112.12		0.091			961	30.86	39

7d	239.53	18.40	61.48	22.56	0.80				1.33	0.58	117.18	0.001	0.085	0.157	673	31.38	52
8a	7.85	0.57	77.50	10.80	0.02	1.10				0.09	2.10				295	7.05	23
8b	4.42	0.69	91.93	12.59		0.04			0.27	0.06	0.34			0.480	359	2.66	19
8c	4.18	0.66	86.24	10.86		0.04			0.19	0.08	0.42	0.003		0.615	339	2.41	14
8d	4.16	0.63	77.85	11.13					0.00	0.17	0.65			1.634	274	3.36	30
9a	10.10	0.15	70.20	4.10		0.54				0.42	3.48				223	19.20	17
9b	6.80	0.52	108.73	6.31	0.01	0.09			0.30	0.21	0.65			0.118	386	10.83	13
9c	6.42	0.51	116.00	5.88	0.01	0.05			0.17	0.17	0.53		0.006	0.138	397	10.03	8
9d	6.52	0.53	80.35	5.93	0.01	0.01			0.29	0.21	0.56			0.100	214	10.99	22
10a	445.00	23.70	135.00	46.20	0.13	1.70	0.480	0.540		1.39	107.00				437	945.00	50
10b	459.90	15.64	368.21	28.82	0.23		0.003	0.187	2.66	0.91	70.78			0.318	771	1067.17	48
10c	444.44	15.13	305.59	51.60	0.23		0.022	0.222	2.72	0.69	60.27		0.021	0.093	790	891.12	26
10d	460.00	15.79	259.59	51.82	0.26				2.57	0.85	77.65				600	1205.83	37
11a	292.00	9.97	103.00	42.20	0.05	3.20	0.210	0.310		0.59	82.00				439	545.00	36
11b	231.82	5.70	152.90	37.35	0.09		0.008	0.145	1.24	0.37	59.83		0.023	0.123	534	415.38	34
11c	236.27	5.71	150.24	37.22	0.10				1.11	0.29	55.44		0.001	0.526	549	397.88	19
11d	220.49	5.36	115.77	34.90	0.11				0.99	0.31	55.88		0.013	0.003	400	406.79	16
12a	900.00	17.70	60.20	19.50	0.23	0.75	0.440	0.570		0.92	957.00				515	254.00	50
12aa	970	38.9	89.3	20.3	0.35		0.076		2.37		1054		0.35		732	304.00	34
12b	963.50	13.75	150.00	14.95	0.40	15.75			0.00	0.87	1003.20			0.039	804	263.31	60
12c	953.56	11.94	120.38	12.13				0.694	1.96	0.66	814.04		0.138	0.144	819	245.94	48
12d	919.29	11.66	109.49	10.69					1.83	0.93	1145.34		0.193	2.342	631	353.87	48
13a	325.00	7.22	168.00	57.50	0.03	0.74	0.190	0.430		1.05	405.00				344	445.00	39
13aa	313	6.81	155	61.7	0.05		0.02		1.48		332		0.07		519	426.00	26
13b	303.37	3.77	218.84	40.06	0.08				1.08	0.34	291.15			0.087	562	349.21	34
13c	313.57	3.91	200.50	48.55	0.10				1.23	0.29	251.59			0.423	572	318.67	28
13d	310.93	3.72	167.23	47.26	0.10				1.26	0.32	298.37		0.041	0.026	386	397.06	32
14a	332.00	27.70	4.32	3.71	0.84	7.40	0.980	1.690		10.20	133.00				790	32.00	68
14c	293.82	18.53	25.84	2.23	0.83		0.094	0.427	0.82	8.05	22.58		0.040	0.037	929	19.07	61
14d	289.32	15.88	13.36	2.36	0.85		0.111	0.377	0.84	0.07	62.38		0.012	0.041	807	80.70	51
15c	166.02	8.50	8.59	0.68	0.46		0.111	0.378	0.14	9.78	9.44		0.047		468	21.64	101

15d	166.51	8.53	8.83	0.74	0.46		0.076	0.188	0.26	12.57	11.84	0.003	0.032	0.116	14	414	27.74	79
16a	122.00	13.20	2.10	1.70	0.10	4.05	0.740	0.570		7.44	12.20				13	260	19.20	95
16c	96.02	7.94	6.38	1.03	0.10		0.101	0.156	0.23	6.30	5.83			0.008		293	10.58	84
16d	90.86	7.74	6.29	1.02	0.11		0.095	0.113	0.24	7.08	6.49	0.003	0.012	0.059		260	11.72	79
17c	193.19	13.12	18.49	1.50	0.40		0.164	0.347	0.36	10.14	10.17	0.005	0.054	0.015		598	23.80	94
17d	193.39	13.27	16.90	1.45	0.41		0.154	0.182	0.35	12.59	12.46	0.004	0.020	0.114	45	429	29.48	80
18a	152.00	13.10	127.00	8.60	0.05	3.84	0.300	nd		3.70	12.20					114	580.00	116
18b	119.87	8.55	168.30	6.91	0.10		0.040	0.228	3.37	3.74	6.48			0.339		115	480.87	101
18c	116.77	8.33	166.66	6.91	0.10		0.032	0.250	3.28	3.33	5.45			0.028		134	407.81	73
18d	116.17	8.24	165.27	6.91	0.09		0.103		3.28	4.07	6.78		0.004			112	519.55	84
19b	136.97	14.75	540.65	27.75	0.38		0.024	0.155	7.83	2.82	6.01			0.074		158	1267.96	92
19c	132.22	12.90	459.22	52.47	0.34				7.95	2.84	5.67					168	1111.44	47
19d	132.47	12.74	475.14	49.59	0.38				8.35	3.44	7.05					154	1402.24	87
20b	138.34	14.72	121.52	3.96	0.15		0.126	0.069	3.63	5.68	7.71			0.002		147	379.40	151
20c	131.61	14.04	114.08	3.77	0.14				3.14	4.79	7.18	0.013	0.006	0.001		156	353.88	123
20d	131.95	14.12	115.04	3.88	0.16				3.23	5.20	7.29		0.006		7	140	353.46	139
21a	235.00	23.10	6.92	1.80	0.24	4.50	1.430	0.530		8.13	26.30					165	332.00	191
21b	195.87	20.52	29.06	5.88	0.27		0.157		0.61	9.36	11.65		0.007	0.012		271	246.37	156
21c	180.55	18.86	22.29	4.77	0.25		0.159		0.66	7.75	9.28		0.022	0.023		252	204.60	134
21d	175.33	18.78	33.43	5.22	0.27		0.135		0.71	10.84	12.64			6.869	14	246	275.35	131

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Reservoir temperature and variations

Reservoir temperature is an important parameter for classifying the genetic types of geothermal systems and for evaluating the geothermal potential of geothermal fields, which can be estimated using geochemical geothermometers. The concentration of solutes in geothermal fluids is a function of the geothermal reservoir temperature. In theory, all chemical reactions controlled by temperature can be used as geochemical geothermometers [19, 20].

Traditionally, cation ratio geothermometers such as Na-K, Na-K-Ca, and K-Mg geothermometers and SiO₂ geothermometers are used to estimate the geothermal reservoir temperature [21-23]. The reservoir temperatures calculated using equations (1–4) are shown in Table 3.

$$\theta_{\text{quartz}}(^{\circ}\text{C}) = \frac{1309}{5.19 - \log[\text{SiO}_2]} -$$

273.15

$$\theta_{\text{NaK}}(^{\circ}\text{C}) = \frac{1217}{1.483 - \log\left[\frac{[\text{Na}]}{[\text{K}]}\right]} -$$

273.15

$$\theta_{\text{NaKCa}}(^{\circ}\text{C}) = \frac{1647}{\log\left[\frac{[\text{Na}]}{[\text{K}]} + \beta[\log(\sqrt{[\text{Ca}]/[\text{Na}]} + 2.06)] + 2.47}\right]} -$$

273.15

(3)

$$\theta_{\text{KMg}}(^{\circ}\text{C}) = \frac{4410}{14.0 - \log\left[\frac{[\text{K}^2]}{[\text{Mg}]}\right]} -$$

273.15

Table 3

Estimated reservoir temperatures of the hot springs in the Simao Basin.

Sample					Sample				
Reservoir temperature (° C)					Reservoir temperature (° C)				
No.	Quartz	Na-K	K-Mg	Na-K-Ca	No.	Quartz	Na-K	K-Mg	Na-K-Ca
1a	91	172	83	176	11a	87	139	52	74
1b	92	129	68	90	11b	85	120	42	48
1c	78	143	70	89	11c	62	119	42	49
1d	91	127	66	128	11d	55	120	41	51
2a	116	151	83	144	12a	102	108	73	121
2b	117	100	68	75	12aa	85	149	92	151
2c	111	115	74	83	12b	111	92	70	90
2d	116	101	68	83	12c	100	86	69	90
3b	85	84	77	105	12d	100	87	70	91
3c	83	78	79	101	13a	91	115	42	56

3d	81	78	79	102	13aa	74	114	40	55
4a	97	101	81	118	13b	85	86	33	33
4b	100	71	66	90	13c	77	86	32	36
4c	67	63	67	86	13d	82	84	31	38
4d	95	63	67	87	14a	117	202	106	197
5a	91	97	91	118	14c	111	180	102	164
5b	88	71	75	94	14d	103	170	97	162
5c	86	67	83	94	15c	138	166	97	153
5d	92	67	82	94	15d	124	166	96	153
6a	83	157	38	28	16a	134	224	96	200
6b	82	142	33	17	16c	128	201	89	170
6c	63	142	33	16	16d	124	204	89	171
6d	77	136	32	21	17c	134	186	98	163
7a	107	207	79	185	17d	125	187	99	165
7aa	99	194	79	164	18a	146	205	75	72
7b	111	193	73	91	18b	138	190	68	51
7c	91	248	83	87	18c	120	190	67	51
7d	104	195	72	163	18d	128	189	67	50
8a	69	191	12	109	19b	133	223	65	46
8b	62	258	14	131	19c	99	215	55	45
8c	51	260	14	131	19d	130	214	55	44
8d	79	255	13	130	20b	162	222	88	75
9a	57	94	-	59	20c	149	223	87	75
9b	48	195	15	107	20d	156	223	87	75
9c	32	198	15	107	21a	177	216	111	196
9d	67	200	16	111	21b	164	221	91	182
10a	102	168	70	149	21c	154	221	92	183
10b	100	139	66	67	21d	153	223	91	180
10c	74	139	58	69					
10d	88	140	59	74					

In Table 3, the reservoir temperatures calculated by quartz geothermometers are 32–177 °C and those by cation geothermometers are 63–260°C (Na-K), 12–91°C (Na-K), 16-200 (Na-K-Ca), respectively, varying over a wide range. The Na-K-Mg triangular diagram divides waters into fully-equilibrated waters, partially-equilibrated waters, and immature waters, which are used to determine whether a fluid has reached water-rock equilibrium [22]. Only fully-equilibrated waters are suitable for use with cation geothermometers. In Fig. 5, most data points for the water samples from the hot springs plot in the area of immature water. Samples No. 2, 3, 4, 5, and 12 are located in the partially-equilibrated area of the triangular diagram. This suggests that the main cation concentrations in the geothermal water and the wall rock have not reached equilibrium due to the addition of a significant quantity of cold water

(shallow groundwater) as the deep hot (thermal) water moves upward. Therefore, cation geothermometers are not suitable for calculating the reservoir temperatures in the study area.

Fig. 5. The Na-K-Mg trilinear equilibrium diagram of the hydrothermal water from the Simao basin.

The calculated saturation index (SI) of various minerals in water as a function of temperature in the Simao Basin suggests that the quartz geothermometer provides more reasonable estimations of the reservoir temperature than cation geothermometers in this area [11]. As mentioned previously, the studied hot spring waters are mixtures of thermal groundwater with shallow cold waters, which lead to a highly dilute silica concentration. Therefore, the temperatures calculated with SiO_2 geothermometers were lower than the most reliable reservoir temperatures. The silica-enthalpy mixing model equation and silica-enthalpy diagram can be used to estimate the proportion of the thermal groundwater and cold waters, as well as the original temperature of the thermal groundwater component, which can be used as the reservoir temperatures [24]. The silica-enthalpy equation was used to calculate the proportion of the cold water during mixing based on the dissolved silica contents and enthalpy values of cold and mixed hot waters [25].

$$H_c \cdot X_1 + H_h(1 - X_1) = H_s \quad (5)$$

$$\text{Si}_c \cdot X_2 + \text{Si}_h(1 - X_2) = \text{Si}_s \quad (6)$$

where H_c is the enthalpy of near-surface cold water, H_h is the initial enthalpy of deep hot water, H_s is the enthalpy of mixed hot water, Si_c is the silica content of near-surface cold water, Si_h is the initial silica content of deep hot water, and Si_s is the silica content of mixed hot water. X_1 and X_2 are the

calculated cold water mixing ratios of the enthalpy and the SiO_2 concentration, respectively. The solution of equations (5) and (6) was calculated using a diagrammatic method (Fig. 6, taking the example of samples 10a-d) because X_1 , X_2 , and H_s are unknown. The relationship between X and temperature was plotted to obtain two curves whose intersection gave the estimated proportion of cold water and the original temperature of the thermal groundwater component. The silica-enthalpy diagram was used to estimate the temperature of the deep thermal groundwater with a plot of silica concentration vs. the enthalpy of water [24]. A line through the characteristic points for the cold (point A) and geothermal (point B) waters, the intersection (point C) of the line, and the quartz solubility curve shows the enthalpy of the deep thermal groundwater (Fig. 7, taking the example of samples 10a-d).

Except for data points 4c, 5c, 7c, 10c, and 12c at lower temperatures, the reservoir temperatures of the mixing model of the silica-enthalpy equation and diagram ranged between 121 °C and 289 °C (Table 4). These values are significantly higher than those of the reservoir temperatures determined by the SiO_2 geothermometer in Table 2. The proportions of cold water mixing ranged from 69% to 98%. There is no intersection point at the plots of samples 1c-d, 6c, 8c, 9a-d, 11c, 14a-d, 16a-d, 18a-d, and 19a-d, indicating that heat was lost before the hot and cold waters mixed. The reservoir temperatures in sampling points 4c, 5c, 7c, 10c, and 12c, which are located approximately 50–150 km southwest of the epicenters of the M5.9 Mojiang earthquake, showed large decreases after the earthquake (Fig. 8). Especially, the reservoir temperatures of sample 10c decreased by ~100 °C after the M5.9 Mojiang earthquake but recovered in 2020 (200–223 °C). The variations in reservoir temperature are similar to those of the M 8.0 Wenchuan earthquake [9]. The reservoir temperature before the Wenchuan earthquake was ~340 °C and decreased to a relatively stable level after the earthquake (220–260 °C).

Fig. 6. Diagram of temperature relative to the proportion of cold water in hot spring sample 10 (X is the proportion of the cold water).

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Fig. 7. The silica-enthalpy diagram of hot spring sample 10

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Fig. 8. Reservoir temperature variations in some springs from the 1980s to 2020.

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Table 4

235

Reservoir temperatures based on the silica-enthalpy mixing model and cold water mixing proportions

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of the hot springs in the Simao Basin.

Sample	Reservoir temperature (° C)		Cold water mixing proportion (%)	Sample	Reservoir temperature (° C)		Cold water mixing proportion (%)
	Silica-enthalpy graph	Silica-enthalpy equation			Silica-enthalpy graph	Silica-enthalpy equation	
1a	226	220	92.6	11a	231	234	94.6
1b	192	194	89	11b	231	228	94.7
1c	-	-	-	11c			
1d	-	-	-	11d			
2a	280	275	91.3	12a	225	218	88.9
2b	-	-	-	12aa	225	219	94
2c	272	263	91.5	12b	227	225	87
2d	-	-	-	12c	188 ↓	192 ↓	84.7
3b	241	258	96.2	12d	200	216	89.2
3c	-	-	-	13a	256	247	94.7
3d	-	-	-	13aa	146	154	90.6
4a	214	203	88.5	13b	-	-	-
4b	194	194	85.3	13c	279	263	97.6
4c	103 ↓	107 ↓	81.7	13d	-	-	-
4d	193	193	87.2	14a	-	-	-
5a	147	148	76.9	14c	-	-	-

5b	142	140	74.7	14d	-	-	-
5c	114 ↓	129 ↓	71.4	15c	252	246	80.9
5d	150	150	77.2	15d	208	206	76
6a	143	151	84	16a	-	-	-
6b	140	149	83.8	16c	-	-	-
6c	-	-	-	16d	-	-	-
6d	121	126	80.3	17c	268	267	85.6
7a	185	184	78.5	17d	239	233	82.7
7aa	154	150	69.2	18a	-	-	-
7b	187	190	78.2	18b	-	-	-
7c	122 ↓	122 ↓	59.3	18c	-	-	-
7d	165	171	76.2	18d	-	-	-
8a	225	256	98.4	19b	-	-	-
8b	217	183	97.9	19c	-	-	-
8c	-	-	-	19d	-	-	-
8d	-	-	-	20b	-	-	-
9a	-	-	-	20c	289	271	81.2
9b	-	-	-	20d	-	-	-
9c	-	-	-	21a	-	-	-
9d	-	-	-	21b	278	263	73.5
10a	190	200	85.9	21c	250	235	69.4
10b	197	208	87.9	21d	246	237	71.1
10c	105 ↓	107 ↓	71.3				
10d	200	223	93.5				

237

238 Analysis of hydrogeochemical characteristics

239 The chemical characteristics of geothermal water in the Simao Basin show that the main ions in the
240 hot spring water mainly come from the dissolution of minerals during the circulation of surface water.
241 The stratum lithology characteristics in the area control the water chemistry characteristics. Previous data
242 provide a clear understanding of the origin and evolution of major ions in thermal groundwater. Na in
243 the hot spring waters was derived from the dissolution of Na-feldspar. Ca^{2+} (Mg^{2+}) and HCO_3^- in the hot
244 spring waters are mainly derived from the dissolution of carbonate minerals, gypsum, and anhydrite in
245 the Triassic rocks. The saline spring flows in the red beds and dissolves large amounts of halite with high
246 Cl^- and Na^+ contents.

247 The existence of LVZs has been revealed by seismic imaging beneath the Simao Basin within the
248 middle-lower crust at a depth of 15–30 km, and is considered to be possible ductile crustal flow [26–28].
249 Ductile crustal flow may be the dominant heat source of the hot springs in the Simao Basin. The reservoir
250 temperatures (121–289° C) were estimated in the Simao Basin. The hot springs with higher reservoir

temperatures ($> 250^{\circ}\text{C}$) were mainly located at the margin of the basin (e.g., sample sites 2, 13, 15, 17, 20, and 21), where the Lancangjiang and Ailaoshan deep faults were well-developed. Fracture is the main channel of hot water circulation, and the deep faults help provide deep heat for the spring waters [29]. Furthermore, in the study area, the fissures were well-developed in the carbonate rocks, while the metamorphic strata exposed in the margin of the basin commonly have a low permeability. As a result, springs emerged in the Ailaoshan metamorphic rocks with higher reservoir temperatures.

Assumptions of earthquake-related hydrogeochemical variation

Two assumptions have often been used to explain earthquake-related hydrogeochemical changes [10]: (i) hydrogeochemical shifts record accelerated water-rock interactions resulting from an increased reactive surface area caused by fracture of the sampled aquifer; or (ii) hydrogeochemical shifts record the mixing of (or switching between) chemically distinct aquifers. This could occur in response to the fracture of a hydrological barrier between aquifers or because of a change in the relative pressures of connected aquifers.

When an earthquake occurs, the pore pressure in rocks is enhanced as a seismic wave propagates through, causing extensive fracture of the wall rock [30]. This increased the rock surface area in contact with groundwater, which resulted in more extensive water-rock interactions. The saturation index (SI) is commonly used in hydrogeochemistry to indicate the chemical states of mineral phases in groundwater. The saturation state of hot springs in the Simao Basin was calculated based on the chemical compositions and physicochemical parameters of the hydrothermal waters via the PHREEQC program package [31]. The SI values of carbonate minerals (calcite and aragonite) exhibited significant changes before and after the Mojiang earthquake (Fig. 9). The SI values of other selected minerals (e.g., gypsum, anhydrite, celestite, and halite) were less than 0, remaining undersaturated. The calcite and aragonite saturation trends are shown in Figure 9. The SI values of calcite and aragonite in almost all undersaturated sampling points reached saturation before the Mojiang M5.9 earthquake, indicating the enhanced dissolution of carbonate rocks. This could explain the observed increases in the concentrations of Ca^{2+} and HCO_3^- during the Mojiang earthquake on 8 September 2018. The water chemistry type in No.7 and 13 changed from $\text{Na-HCO}_3\text{-Cl}$ to Na-Ca-HCO_3 , $\text{Na-Ca-Cl-SO}_4\text{-HCO}_3$ to $\text{Na-Ca-HCO}_3\text{-Cl-SO}_4$, which also indicates that Ca^{2+} and HCO_3^- dissolution was in-progress. After the earthquake, the SI ratios continued to increase to oversaturation, indicating that precipitation occurred in hot springs, and the dissolved ion

concentration decreased. The SI values decreased and recovered in 2020. This progressive re-equilibration by water-rock interactions explained why the Ca^{2+} and HCO_3^- contents returned to their pre-seismic levels and why the water chemistry type in No.7 and 13 also recovered.

Fig. 9. Variations in the SIs of calcite and aragonite in the hot springs from the 1980s to 2020.

The rupture of hydrological barriers or permeability changes are probable causes of variations in ion concentrations and reservoir temperature. Under the N–S-trending tectonic compression stresses, the local stress concentration may give rise to a new fracture and induce moderately-large earthquakes like the Mojiang M5.9 earthquake [32]. New fractures were created during the Mojiang earthquake, which caused the permeability to greatly increase. The obvious increases in the concentrations of Ca^{2+} and HCO_3^- may be attributed to a second fluid rich in Ca^{2+} and HCO_3^- from the underlying carbonate strata. The variation may correlate with the contribution of deep fluids. Under the Simao-Pu'er seismic zone, strong low-velocity zones are visible, suggesting the existence of an upwelling asthenosphere in the uppermost mantle. High He isotope signatures ($^3\text{He}/^4\text{He} = 5.75\text{--}8.36 \text{ Ra}$; mantle-derived He $>70\%$) have been observed in this region [33]. Increased $^3\text{He}/^4\text{He}$ ratios in hot springs were observed before $M > 4$ earthquakes in the Simao-Pu'er seismic zone, indicating that much more deep fluid was added to these springs.

Moreover, similar to the explanation of the M 8.0 Wenchuan-related reservoir temperature change [9], variations in reservoir temperature after the Mojiang earthquake may have been caused by the entrance of cold shallow groundwater into the reservoir, which participated in deep circulation; however, the clogging of fractures prevented the entry of shallow cold groundwater, and the reservoir temperature increased.

Conclusions

We studied the hydrochemical characteristics of 21 thermal springs from 2018 to 2020 in the Simao Basin. These water samples were roughly divided into three groups: saline spring waters, HCO_3^- -rich spring waters, and SO_4^{2-} -rich spring waters. Stratum lithology characteristics in the area controlled the water chemistry characteristics. Ca^{2+} (Mg^{2+}) and HCO_3^- in the hot spring waters were mainly derived from the dissolution of carbonate minerals, gypsum, and anhydrite in Triassic rocks. The saline springs flowed in the red beds and dissolved a large amount of halite with high Cl^- and Na^+ contents. The Ailaoshan metamorphic rocks contain pyrite, which may increase the SO_4^{2-} content in the hot spring waters. The reservoir temperatures (121–289° C) were estimated in the Simao Basin. It is speculated that the ductile crustal flow could be the dominant heat source of the hot springs of Simao Basin. The hot springs with higher reservoir temperatures ($> 250^\circ\text{C}$) were mainly located in the margin of the basin, which may correlate with nearby deep faults that provide deep heat and metamorphic rocks with a low permeability.

During the study period, the 2018 Mojiang M5.9 earthquake occurred in the study area and caused significant hydrochemical changes. The concentrations of Ca^{2+} and HCO_3^- in most springs increased obviously before the Mojiang M5.9 earthquake but decreased after the earthquake. The chemistry types of the two spring samples also changed before the earthquake and eventually recovered to their pre-seismic types. The reservoir temperature decreased after the earthquake. These hydrogeochemical variations might be attributable to accelerated water-rock interactions and/or the mixing of a second fluid due to the earthquake.

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Authors' contributions

Qilin Li: Conceptualization, Investigation, Writing - original draft, Visualization. Ciping Zhao: Methodology, Data curation. Yun Wang: Investigation, Discussion. Yiying Zhou and Hua Ran: Investigation.

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Availability of data

All underlying data of the research study are included in the manuscript in the form of Tables 1–2.

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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421

Figures

Figure 1

Topographic map of the study area (a) and schematic tectonics and spring sites in the Simao Basin (b; modified from Zhang et al.) [12]. Abbreviations: F1 = Lancangjiang fault, F2 = Wuliangshan fault, F3 = Ailaoshan fault, F4 = Mohei fault. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors

Figure 2

Piper diagram (a) and Schoeller diagram (b) of the geothermal waters. Process (black circles) indicating the changes before and after the Mojiang earthquake.

Figure 3

Relationship plots of major ions of the spring water in the Simao Basin.

Figure 4

Hydrogeochemical changes of the thermal springs from the 1980s to 2020.

Figure 5

The Na-K-Mg trilinear equilibrium diagram of the hydrothermal water from the Simao basin.

Figure 6

Diagram of temperature relative to the proportion of cold water in hot spring sample 10 (X is the proportion of the cold water).

Figure 7

The silica-enthalpy diagram of hot spring sample 10

Figure 8

The silica-enthalpy diagram of hot spring sample 10