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Hydrogeochemical Characteristics and Geothermal Potential in Western Yunnan, southwestern China

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ABSTRACT

Western Yunnan region is a renowned high-temperature geothermal zone in southwestern China. Tectonically, it lies within a structural triangle formed by the collision between the rapidly uplifting Tibetan block to the west and the stable Yangtze plate block to the east. The region exhibits significant west-to-east zonation: moving from Tengchong area, which currently hosts a deep-seated magma chamber, through the Lancang region characterized by widespread Mesozoic granites, to the Eryuan and Honghe county areas dissected by the Red River Fault Zone. The characteristics of geothermal springs show pronounced regional variations. To better understand the genesis of geothermal energy and assess its resource potential, we selected representative hot springs in western Yunnan and studied their hydrogeochemical and isotopic composition, as well as spring water characteristics. Our findings indicate that: (1) Three reservoir types are identified, corresponding to different structural zones in the Western Yunnan. The main reservoir types include fractured carbonates and overlying clastic rocks in the Eryuan area, granite and metamorphic rocks in the Lancang area, and carbonate and metamorphic types in the Tengchong-Dehong area. (2) The chemical characteristics of the geothermal springs clarify their genetic types, which also vary across western Yunnan. (3) A geothermal model is established, characterized by a eastward decrease in tectonic activity intensity, transitioning from volcanism-dominated to granite-dominated and fault-dominated regimes. Specifically, the Dehong area represents a volcanic rock-controlled thermal fault-circulation type; the Lancang area is a granite-controlled thermal fault-circulation type; and the Eryuan and Honghe areas are deep-circulation convection types controlled by deep-seated faults.

Keywords: Western Yunnan; Geothermal genesis; Hydrogeochemistry

INTRODUCTION

Western Yunnan Province, southwestern China hosts abundant high-temperature geothermal resources, characterized by their diverse reservoir types and complex formation mechanisms. Tectonically, the region lies within a structural triangle formed by the collision between the rapidly uplifting Tibetan block to the west and the Yangtze block to the east.

From west to east, the tectonic characteristics exhibit significant zonation. The westernmost Tengchong-Dehong area, strongly influenced by the collision from Tibetan block, experiences frequent tectonic activity and has undergone multiple phases of volcanic eruptions. These eruptions began in the Late Miocene and peaked in the Late Pleistocene, with magma chambers of varying sizes present at depths of 10 km to 50 km (Li and Zhang 2011; Fan et al. 2025a, 2025b). Further east, the Lancang area is situated within the Changning-Menglian tectonic belt. Along its eastern margin lies the north-south trending Lincang granite, the largest exposed granite in western Yunnan, covering an area of over 7,400 km^2 (Peng et al. 2006). To the east lie the Eryuan and Honghe County areas, distributed along the Red River Fault Zone. The Red River Fault originates in Eryuan to the north and extends southeastward through the Honghe area to the Sino-Vietnamese border, serving as a boundary tectonic belt between the Yangtze Platform and the Indochina Block (Shao et al. 2022) (Fig. 1).

As a key component of the Sanjiang Fold Belt, the high-temperature geothermal zone in western Yunnan is closely linked to deep dynamic processes resulting from plate collisions. Previous studies have categorized geothermal heat sources in the region into three types: (1) volcanic geothermal systems, where residual heat from Cenozoic magmatic activity provides the main heat source; (2) radiogenic heat source systems in tectonic zones, where heat is continuously released by the decay of radioactive elements (U, Th, K) in enriched rocks, such as granites; and (3) frictional heat systems in fault zones, where shear heating from tectonic movement

creates localized thermal anomalies. The deep faults in western Yunnan connect heat sources and circulating water, forming various geothermal spring systems (Chen et al. 2024, 2025).

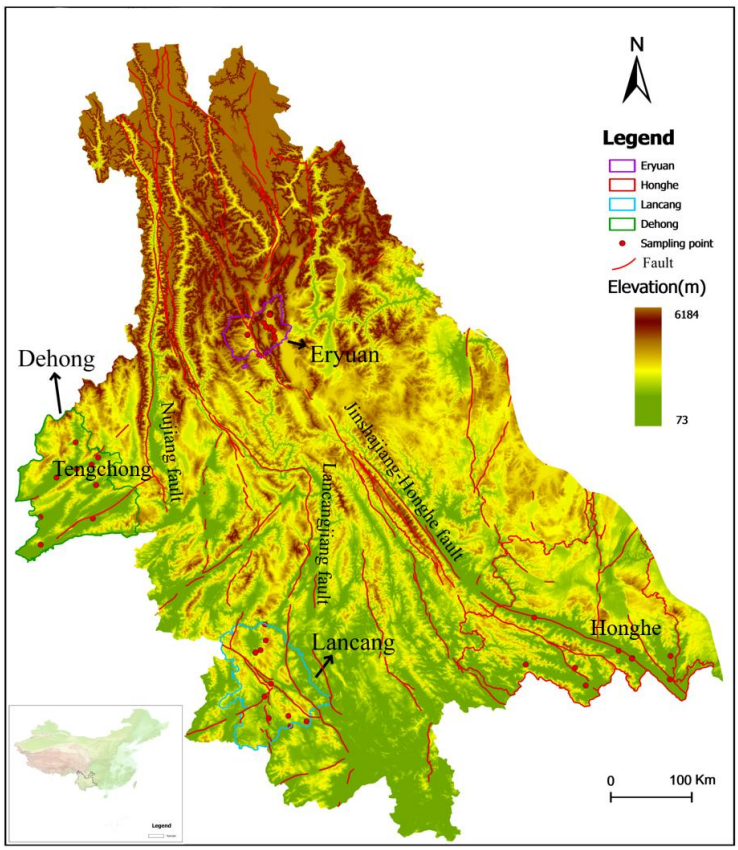


Figure 1. Geomorphic map and spring sampling in western Yunnan province.

1 SAMPLING AND PROCESSING

A total of 28 water samples were collected from four geothermal areas in Western Yunnan: Eryuan, Honghe, Lancang, and Dehong. To ensure sample integrity, all containers were pre-rinsed three times with the target water prior to collection. For surface water, cold springs, and artesian springs, sampling was conducted at stable flow points free of suspended solids, with containers submerged below the water surface. For borehole hot water, samples were collected only after continuous discharge had stabilized the water temperature. After collection, all containers were immediately sealed with hot wax and labeled with sample numbers and collection times.

Field parameters—including water temperature, pH, oxidation-reduction potential (ORP), dissolved oxygen, and conductivity—were measured on-site using a portable Hach HQd analyzer. Laboratory analyses followed Chinese national standards (GB/T 5750.4-2006). Cations such as potassium, calcium, and sodium were determined using an Optima 5300DV inductively coupled plasma optical emission spectrometer (ICP-OES), while anions were analyzed with a Dionex Integrion high-pressure ion chromatograph (HPIC).

To enhance the dataset and support robust interpretation, these field and laboratory results were supplemented with historical chemical data from the *Yunnan Gazetteer Volume 25: Hot Springs*. In total, 44 water samples were compiled for comprehensive geochemical analysis.

2 ANALYSIS OF HYDROCHEMICAL CHARACTERISTICS AND DISCUSSION

2.1 Analysis of Hydrochemical Processes of Geothermal Water

Ionic composition analysis (Fig. 2) reveals the dominance of Na^+ among cations, following the order $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, while HCO_3^- prevails among anions with the sequence: $HCO_3^- > Cl^- > SO_4^{2-}$. Notably, water samples from the Eryuan and Honghe areas exhibit considerable variation in both cation and anion concentrations. This may be related to the control of the Red River Fault, where more complex water-rock interactions occur as water circulates along the fault. The Piper diagram visually represents the hydrogeochemical facies of each region (Fig. 3). The cation concentrations indicate a sodium-dominant composition, with minor amounts of Ca^{2+} and Mg^{2+} in

Eryuan and Honghe. Anion concentrations are mainly distributed in the lower left corner of the anion triangle, reflecting a bicarbonate-dominant composition. Notably, SO_4^{2-} levels in Eryuan and Honghe are relatively elevated compared to those in Lancang and Dehong.

The Schoeller classification analysis reveals that the overall water types in the study area are predominantly HCO_3-Na, HCO_3·SO_4-Na, and HCO_3·SO_4-Na·Ca waters. Specifically: In Eryuan, the water types are primarily HCO_3·SO_4-Na·Ca, HCO_3-Na, and HCO_3-Ca·Mg.In Honghe, the dominant types include HCO_3-Ca·Mg, HCO_3·SO_4-Na, and HCO_3-Na.The Lancang region is characterized by HCO_3·SO_4-Na and HCO_3-Na waters, with some minor occurrences of HCO_3-Na·Ca.In Dehong, HCO_3-Na is the primary water type, with smaller contributions from HCO_3·Cl·SO_4-Na and HCO_3-Ca.

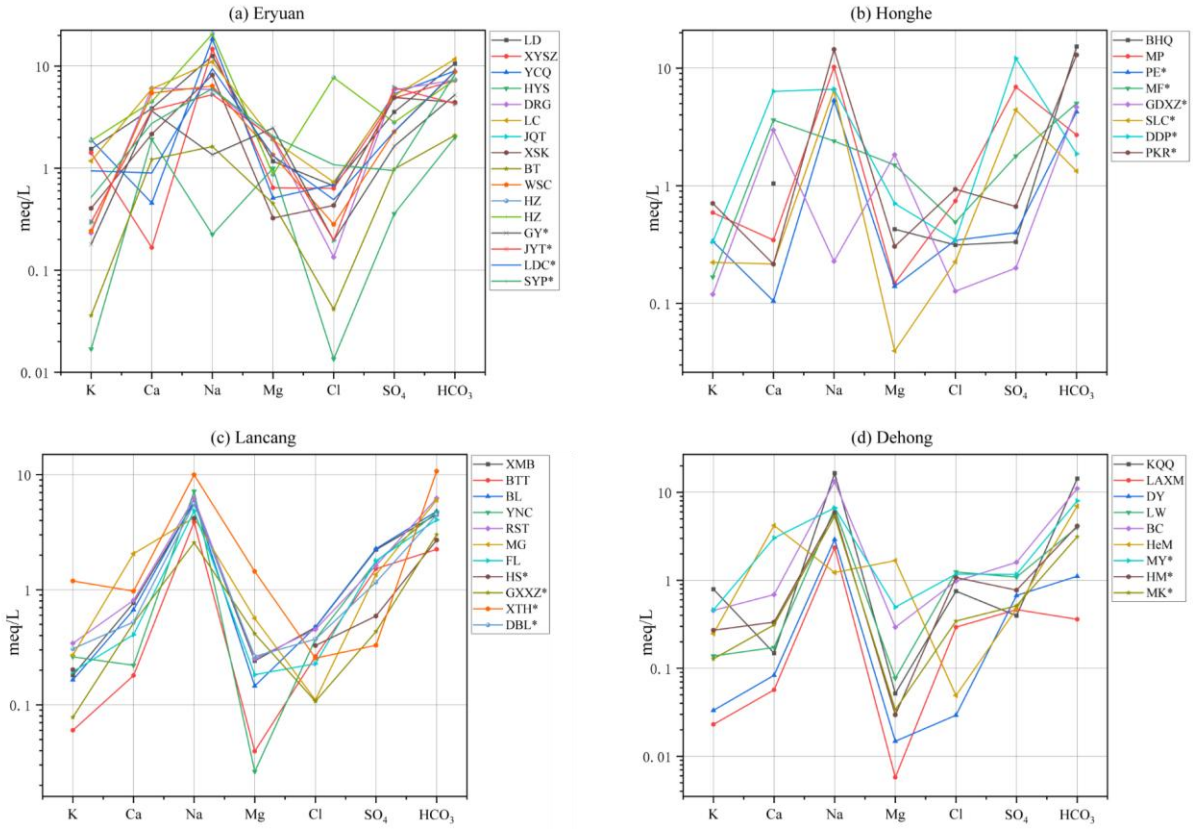


Figure 2. Schoeller diagram of main ions in thermal water.

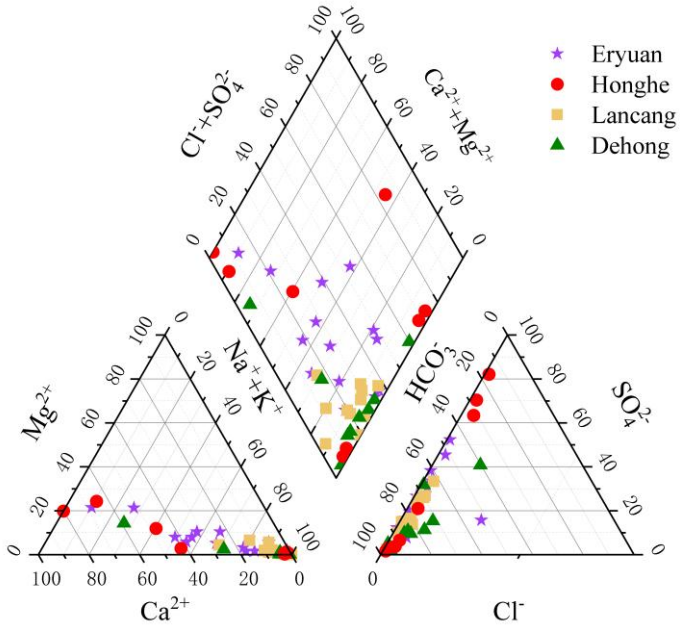


Figure 3. Piper diagram demonstrating the hydrochemical compositions of thermal water.

In general, the major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-) in geothermal waters originate from mineral dissolution processes(Tian et al. 2018). Atmospheric precipitation in Yunnan typically exhibits water types dominated by HCO_3-Ca, HCO_3-Na, or HCO_3-Na·Ca. However, the presence of HCO_3·SO_4-Na and HCO_3·SO_4-Na·Ca in the study samples indicates additional SO_4^{2-} sources.

Examination of the Ca^{2+}/SO_4^{2-} molar ratio (Fig. 4a) reveals that some water samples—particularly from Eryuan—plot along the 1:1 dissolution line, while the majority fall on either side. This distribution suggests the influence of cation exchange processes and carbonate dissolution contributing to Ca^{2+} inputs.

The Ca^{2+}/Mg^{2+} plot (Fig. 4(b)) shows that most samples from the four regions fall below the dissolution equilibrium line, indicating dominant calcite dissolution. A small number of samples lie close to the equilibrium line, suggesting dolomite dissolution, especially in select samples from Eryuan and Lancang. Some samples even plot above the line, indicating Ca^{2+} consumption, likely resulting from the combined effects of silicate dissolution and cation exchange. Additional evidence (Fig. 4(c)) supports the simultaneous presence of silicate dissolution and cation exchange processes. The Chloride-Alkali Index (CAI) (Fig. 4(d)) confirms that cation exchange occurs, where Na^+ and K^+ ions replace Ca^{2+} and Mg^{2+} ions in surrounding rock matrices.

In conclusion, based on the ion analysis and geological background of the studied areas, all four regions exhibit varying degrees of silicate dissolution and cation exchange. These processes contribute to the sodium-dominated cationic composition of geothermal water. Carbonate dissolution dominates rock-water interactions in Eryuan, while silicate dissolution is most significant in Lancang. In Honghe and Dehong, both carbonate and silicate dissolution processes are evident.

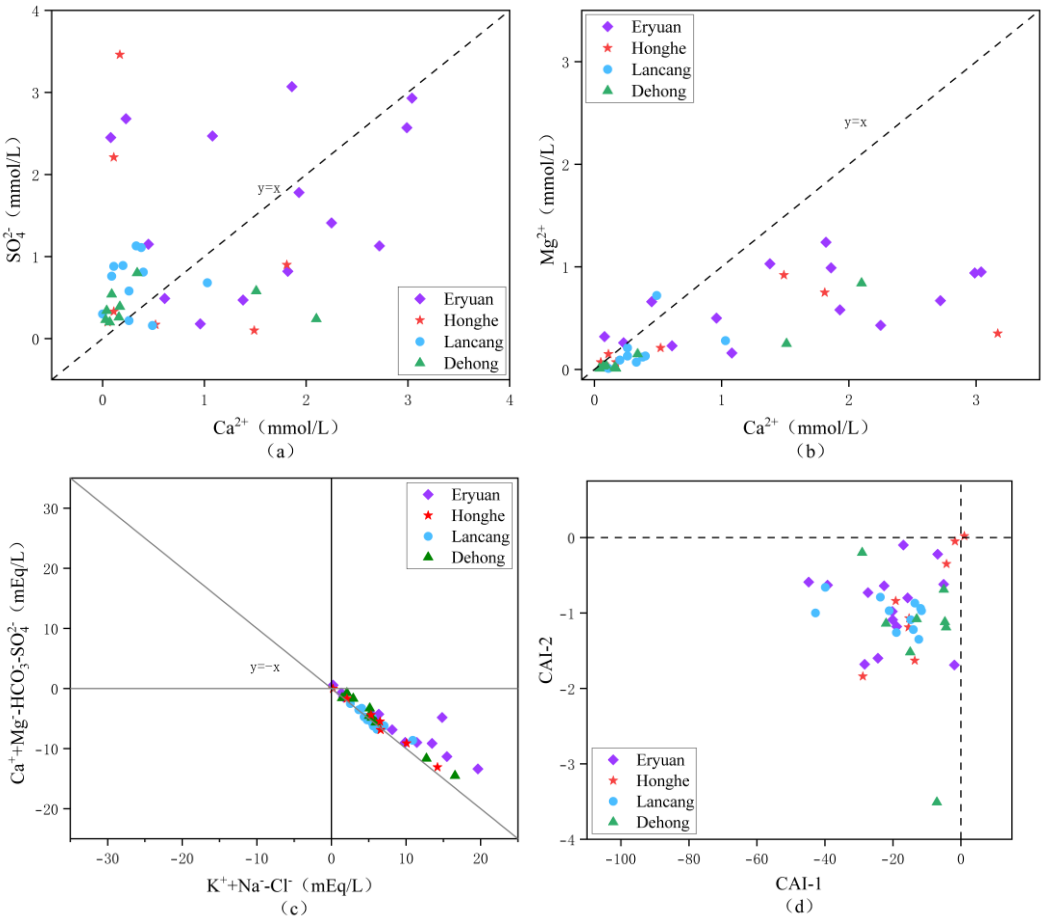


Figure 4. Diagram of Ca^{2+} /SO_4^{2-} relationship (a); Diagram of Ca^{2+}/Mg^{2+} relationship (b); Na^{+}+K^{+} -Cl^{-} versus Ca^{2+}+Mg^{2+} - SO_4^{2-}-HCO_3^{2-} of water samples (c); and CAI-1 versus CAI-2 of water samples (d).

2.2 Water Recharge Sources and Elevation Analysis

Comparing the regional δ^2H and $\delta^{18}O$ values with the local meteoric water line helps infer the recharge source and elevation of the hot water (Luo et al. 2017). The Global Meteoric Water Line (GMWL), the national meteoric water line, and regional precipitation lines for the four study areas were plotted. The δ^2H and $\delta^{18}O$ values of the water samples were projected onto these precipitation lines (as shown in Figure 5). The analysis reveals that the geothermal waters in all four regions lie along their respective regional meteoric water lines, suggesting that the primary recharge source is atmospheric precipitation. However, in the Eryuan area, a notable $\delta^{18}O$ shift was observed, indicating strong water-rock interaction.

Due to the altitude effect on hydrogen and oxygen isotopes, isotopic values in atmospheric precipitation decrease as elevation increases(Blasch and Bryson 2007). In this study, recharge altitudes were calculated using δ^2H values based on the following equation:

$$H = \frac{\delta^2H_G - \delta^2H_P}{K} + h$$

Where, H represents the Recharge altitude (m); δ^2H_G is the δ^2H value in the geothermal water sample (‰); δ^2H_P is the δ^2H value in the atmosphere of the study area (‰); K is the altitude gradient of δ^2H in meteoric precipitation (‰/100 m); h is the elevation of the sampling point (m). The δ^2H values in atmospheric precipitation in the Eryuan area range between -120‰ and 23.7‰ (Liu et al. 2006); in the Honghe area, they range between -152‰ and 52‰, with an average value of -51‰ (Li et al. 2016); in the Lancang and Dehong areas, the average δ^2H values in atmospheric precipitation are 28.41‰ and 36.21‰, respectively (Zhang et al. 2012). The value of K was taken as the hydrogen and oxygen isotope elevation gradient for the Southwest China region, with a value of -2.5‰/100 m(Chen et al. 2024).

Calculation results show that the average recharge elevation for the Eryuan area is 3,500 m, 4,745 m for the Honghe area, 5,235 m for the Lancang area, 4,770 m for the Dehong area. Given that the altitude in Yunnan

Province ranges from 93 m to 6,184 m, these results suggest mountain precipitation as the primary recharge source for the geothermal waters.

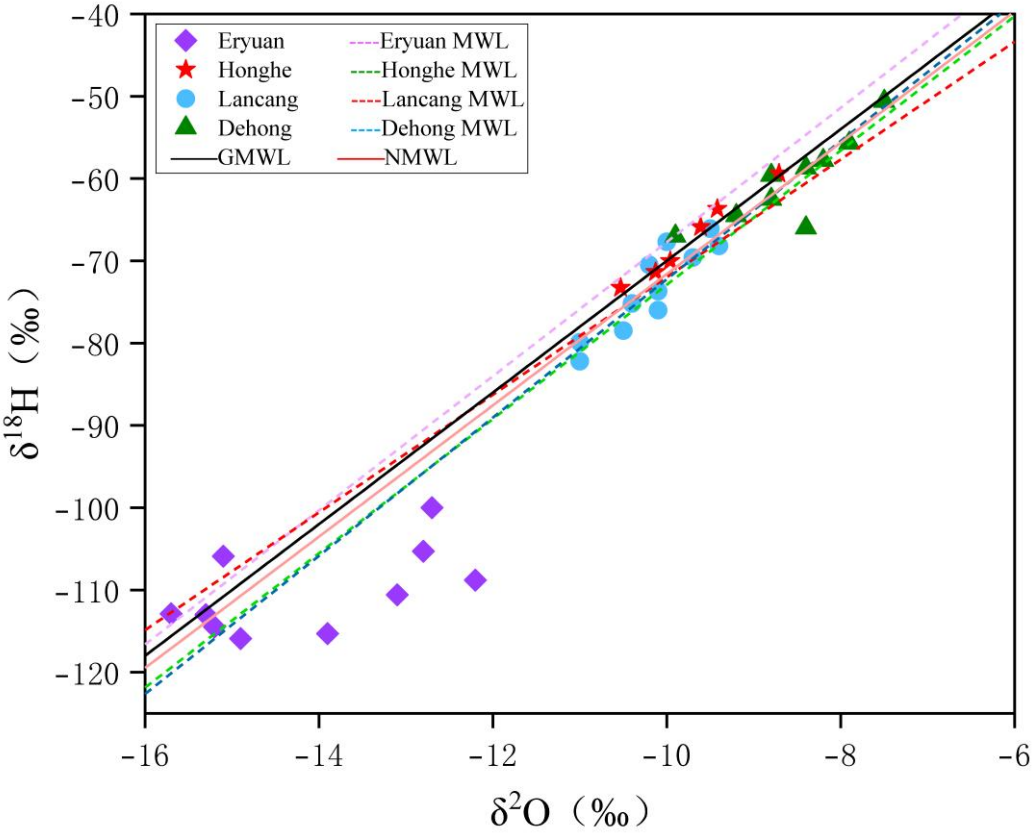


Figure 5. Relationship between the δD and $\delta^{18}O$ of water samples.

2.3 Geothermal Reservoir Temperature and Water Circulation Depth Estimation

Based on the principle of water-rock equilibrium, geochemical thermometers have become a key technical method for estimating reservoir temperatures due to their well-defined physicochemical mechanisms and broad applicability (Bengu, 2021). Giggenbach cation ternary diagram (Fig. 6) shows that the sample points are predominantly distributed in the Mg^{2+} dominant region. This distribution indicates that the geothermal waters from the Eryuan, Honghe, Lancang, and Dehong areas are generally in the kinetically immature stage of water-rock interaction or due to serious mix of cold water. Therefore, conventional cation-based thermometers, such as Na-K and K-Mg, are less applicable to calculate the reservoir temperature (Giggenbach 1988). Saturation indices for chalcedony, quartz, calcite, amorphous silica, gypsum, and halite were computed using PHREEQC software. The analysis showed that most water samples were in equilibrium with chalcedony and amorphous silica, making these suitable geothermal thermometers. However, results from classic quartz geothermometers showed inconsistencies (e.g., temperatures lower than actual water sample temperatures), necessitating the use of improved SiO_2-based geothermometers for final temperature estimates.

The calculation results are shown in Table 1: The maximum temperature of the geothermal reservoir in the Eryuan area is 152.9°C, the minimum temperature is 81.2°C, and the average temperature is 123.7°C; in the Honghe area, the maximum temperature is 177.2°C, the minimum temperature is 66.3°C, and the average temperature is 132.3°C; in the Lancang area, the maximum temperature is 158.7°C, the minimum temperature is 99.1°C, and the average temperature is 133.1°C; in the Dehong area, the maximum temperature is 163.7°C, the minimum temperature is 106.7°C, and the average temperature is 132.1°C. The temperature ranges between the maximum and minimum values in the Eryuan and Honghe areas are relatively large, which may be related to the development of deep-seated faults in the region—geothermal water circulates over a different depth range in different section along the faults. In the Dehong area, the geothermal reservoir temperatures are generally high, with the minimum temperature exceeding 100°C, likely due to the presence of magma chambers in the region.

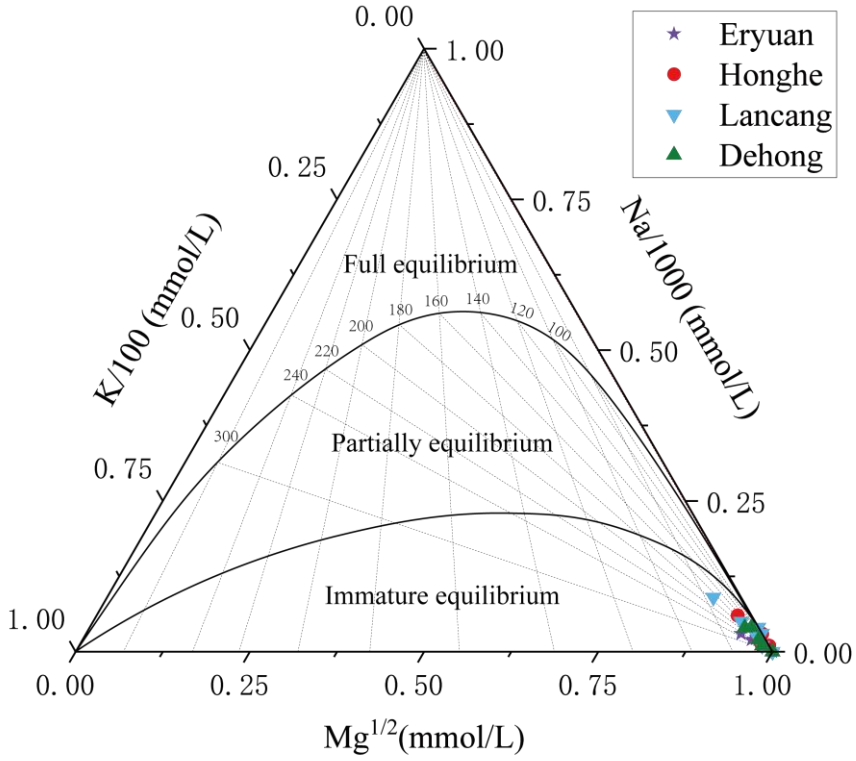


Fig 6. Na-K-Mg Ternary Diagram of Geothermal Water Samples from Typical Areas in Western Yunnan

The circulation depth of geothermal water is positively correlated with reservoir temperature. Combining geothermal gradient data and reservoir temperature estimates, circulation depths were calculated for all four regions using the following formula (Lu et al. 2018):

$$D = \frac{T_R - T_C}{\Delta t} + h$$

Where D is the circulation depth (m), T_R is the reservoir temperature (°C) – the calculation uses results from the silica geothermometer in this process, T_C is the temperature of surface cold water (°C)

As mentioned as above, the geothermal water in the four regions (Eryuan, Lancang, Dehong, and Honghe) is primarily recharged by atmospheric precipitation. The average water temperature of cold spring points in these four regions is 21°C, therefore, T_C is taken as 21°C. Δt is the geothermal gradient (°C/100 m), The average geothermal gradient in the Eryuan area is 2.49°C/100 m; in the Honghe area, it is 2.3°C/100 m; in the Lancang area, it is 4.018°C/100 m; and in the Dehong area, it is 4.5°C/100 m. h is the thickness of the constant temperature zone, with an average thickness of 20 m. The calculated minimum circulation depth for the Eryuan area is 2,436.3 m, maximum is 5315.5 m, and average is 4,143.7 m; for the Honghe area, minimum is 1,988.2 m, maximum is 6,809.6 m, average is 4,857 m; for the Lancang area, minimum is 1,964.2 m, maximum is 3,446.4 m, average is 2809 m; for the Dehong area, minimum is 1,925.5 m, maximum is 3,192 m, average is 2,487.9 m.

Table 1. Calculation results of Geothermal Reservoir Temperature by different methods

Area	Sample ID	SiO2 (mg/L)	$T_{Quartz1}$ (℃)	$T_{Quartz2}$ (℃)	$T_{\alpha\text{-Cristobalite}}$ (℃)	$T_{Chalcedony}$ (℃)	T_{SiO2} (℃)
Eryuan	LD	99.1	136.69	132.29	86.05	109.93	136.72
	HYS	131	152.86	145.82	102.40	127.98	152.86
	LC	75	121.73	119.63	71.09	93.47	121.95
	JQT	61.6	111.80	111.15	61.25	82.66	112.22
	XSK	123	149.10	142.69	98.58	123.76	149.08
	BT	60.3	110.76	110.26	60.22	81.53	111.19
	WSC	84.4	127.93	124.90	77.28	100.27	128.06
	HZ	115.9	145.61	139.77	95.05	119.86	145.59
	GY*	30.7	80.36	83.89	30.54	49.06	81.17

	JGL*	56.2	107.34	107.32	56.85	77.84	107.85
	LDC*	99.1	136.69	132.29	86.05	109.93	136.72
	SYP*	48.2	100.11	101.09	49.75	70.05	100.74
Honghe	BHQ	85	128.31	125.22	77.66	100.68	128.43
	MP	191	176.84	165.60	127.02	155.25	177.16
	PE*	95.4	134.58	130.52	83.94	107.60	134.63
	MF*	50.2	102.00	102.72	51.60	72.08	102.60
	GDXZ*	21.25	65.74	70.99	16.48	33.75	66.27
	SLC*	108	141.54	136.37	90.94	115.32	141.54
	DDP*	116	145.66	139.82	95.10	119.91	145.64
	MPR*	191	176.84	165.60	127.02	155.25	177.16
	PKR*	67.7	116.50	115.17	65.90	87.76	116.82
Lancang	XMB	144	158.63	150.61	108.29	134.49	158.67
	BTT	89.3	130.97	127.47	80.31	103.61	131.06
	BL	96.5	135.21	131.05	84.57	108.30	135.25
	YNC	136	155.12	147.70	104.71	130.53	155.14
	RST	57.5	108.45	108.27	57.94	79.03	108.93
	MG	46.5	98.46	99.66	48.13	68.28	99.12
	FL	126	150.53	143.88	100.04	125.36	150.52
	HS*	114	144.65	138.97	94.08	118.78	144.64
	GXXZ*	47.4	99.34	100.42	48.99	69.23	99.99
	XTH*	115	145.15	139.39	94.59	119.35	145.14
	DBL*	96.5	135.21	131.05	84.57	108.30	135.25
Dehong	KQQ	156	163.64	154.75	113.42	140.17	163.74
	LAXM	66.9	115.90	114.66	65.31	87.11	116.24
	DY	77.7	123.57	121.19	72.92	95.48	123.76
	LW	66.9	115.90	114.66	65.31	87.11	116.24
	BC	87.5	129.87	126.54	79.21	102.40	129.97
	HeM	54.9	106.22	106.36	55.75	76.63	106.75
	MY*	79.9	125.03	122.44	74.38	97.08	125.20
	HM*	153	162.41	153.74	112.16	138.78	162.50
	MK*	113	144.14	138.54	93.56	118.22	144.13

2.4 Geothermal system formation mechanisms in Western Yunnan

The geothermal system in Eryuan and Honghe area features a fault-controlled deep-circulation convective geothermal system characterized by ample groundwater recharge, well-developed carbonate reservoirs, heating through deep geothermal gradients, and significant thermal conduction and fluid transport along faults (Fig. 7).

The geothermal system in Lancang exhibits a shallow-circulation, fracture-dominated local thermal convection pattern within granite bodies, characterized by relatively low water pressure, low flow rates, and less-developed reservoir property. The primary heat source is deep geothermal gradient heating, supplemented by additional radioactive heat generation from granite. Due to limited recharge sources and significant fault control, the scale of groundwater flow in this system is relatively small, with limited driving force, resulting in relatively low surface hot spring flow rates but relatively stable water temperatures.

The geothermal system in Tengchong–Dehong area belongs to a structurally controlled thermal convection geothermal system heated by deep magma chambers, in addition to deep geothermal gradient. Groundwater circulation and thermal flow ascent are strictly controlled by regional fault structures.

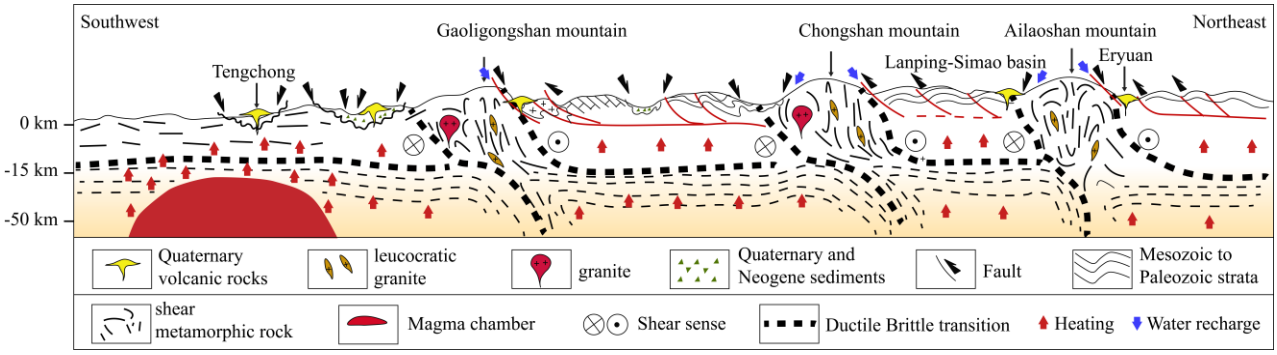


Figure 7. Diagram of geothermal system formation mechanisms in Western Yunnan (magma chamber extents based on Li and Zhang, 2011; Fan et al., 2025a, 2025b).

3 CONCLUSIONS

The geothermal waters in the Eryuan, Honghe, Lancang, and Tengchong-Dehong areas of Yunnan are mainly of the HCO_3-Na, $HCO_3 \cdot SO_4$-Na, and $HCO_3 \cdot SO_4$-Na·Ca types, with notable variations among the different regions. Water chemistry in these areas is governed by the dissolution of carbonate and silicate minerals, as well as cation exchange, and is thus strongly correlated with local lithology. This geological control is reflected in the dominant reservoir rock types: fractured carbonates in Eryuan, granite and metamorphic rocks in Lancang, a mix of carbonate and metamorphic rocks in Dehong, and carbonate with clastic rocks in Honghe.

Meteoric precipitation serves as the primary recharge source for geothermal waters in these typical areas of Western Yunnan. Estimated circulation depths vary regionally: 2,436–5,315 m in Eryuan, 1,964–3,446 m in Lancang, and 1,926–3,192 m in the Tengchong-Dehong area.

From west to east, a geothermal fluid control model is formed, dominated by volcano-intrusion-fault with gradually decreasing intensity of tectonic activity. Specifically, the Tengchong-Dehong area features a magma chamber-controlled thermal fault-circulation type; the Lancang area features a granite-controlled thermal fault-circulation type; the Eryuan-Honghe areas feature deep fault-controlled deep-circulation convection types.

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