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and Mixing Processes**

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Code availability (software application or custom code)

The code during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contributions (optional: please review the submission guidelines from the journal whether statements are mandatory)

GW contributed to the conceptualization, methodology, software and original writing. Resources preparation, data curation and funding acquisition were performed by GW, JM, SZ, MY, and LC. AJM and WR contributed to several data visualizations, revisions and discussions. The first draft of the manuscript was written by GW and all authors

23 commented on previous versions of the manuscript. All authors read and approved the
24 final manuscript.

Abstract

Hydrogeochemical investigations can effectively elucidate the circulation and controlling mechanisms of deep geothermal fluids, thereby complementing conventional geological and geophysical surveys. In the Salt Lake geothermal field of the southern Yuncheng Basin within Fenwei Rift, deep water-rock interactions and evolutionary processes remain poorly understood, limiting the further exploration and sustainable utilization of its geothermal resources. This study presents the first hydrogeochemical characterization of geothermal waters collected from deep boreholes (>2,000 m) to constrain the origin and evolutionary mechanisms of the concealed, high-salinity geothermal system. The Piper diagram shows that the geothermal waters are characterized by the Cl-Na type and have a high mean total dissolved solids concentration of 19,447 mg/L, substantially exceeding those reported for other sub-basins of Fenwei Rift. The Gibbs Diagram and molar ratio analyses indicate that the hydrochemical compositions are primarily controlled by silicate-mineral dissolution, cation exchange, and the dissolution of halite and mirabilite. In particular, the halite and mirabilite dissolution, which potentially precipitated during the Paleogene, appears to be a major contributor to the extremely high salinity. The $\delta^{18}\text{O}$ - δD relationship indicates extensive water-rock interaction and meteoric recharge from the northern Gu Mountain and southern Zhongtiao Mountain, with estimated recharge elevations of 894-973 m. Silica-enthalpy analysis reveals widespread mixing (30%-67%) with shallow cold water, and the contribution exceeds 60% in samples near a concealed NW-

46 trending fractured zone in the eastern part of the study area. The reconstructed reservoir
47 temperature prior to cold-water mixture is 107–155 °C, indicating that the Salt Lake
48 geothermal system is a moderate- to low-temperature system. These hydrogeochemical
49 findings clarify the circulation, salinization and structural control of the concealed
50 geothermal system and provide direct implications for its future exploration and
51 sustainable utilization.

52 **Keywords:** Hydrogeochemistry; Mixing process; Reservoir temperature; Salt Lake
53 geothermal field, Yuncheng Graben Basin

1 Introduction

As global warming and air pollution intensify, the demand for renewable and sustainable energy sources has become increasingly urgent. Geothermal energy has attracted significant attention due to its weather independence, consistency, base load and untapped reserves (Li et al. 2015b; Soltani et al. 2019; Nkinyam et al. 2025). In China, moderate- to low-temperature geothermal resources are predominantly abundant and are used mainly for direct applications (Wang et al. 2017; Jiang et al. 2022). The Cenozoic Fenwei Rift stands out with substantial geothermal potential, where high-, medium-, and low-temperature reservoirs have been discovered to date (Zhou et al. 2022; Liu et al. 2025). Exploring and harnessing these potential reservoirs is of great significance for Shanxi's economic transformation and development.

The Yuncheng Basin, located in the southern Fenwei Rift, contains several types of geothermal reservoirs, including sandstone-type reservoirs in the Salt Lake district, carbonate-dominated reservoirs in Linyi and Hejin, and metamorphic gneiss-related reservoirs in Jishan and Xinjiang (Liu et al. 2025; Wu et al. 2026a). The Salt Lake geothermal field represents one of the principal geothermal areas investigated by drilling, geophysical surveys, and hydrogeochemical investigations. More than 20 geothermal wells were drilled in the urban Salt Lake district between 2008 and 2017, primarily for local direct heating. These wells consistently encountered sandstone-type layered thermal reservoirs, with maximum well-log temperatures of approximately 120 °C at depths of about 3,000 m (Wu et al. 2025). Geophysical techniques, including

75 reflection seismic and microtremor surveys, have been employed to delineate deep
76 structures and thermal anomalies in urban environments, providing valuable insights
77 into the geothermal potential in this concealed region (Wang et al. 2025; Wu et al. 2025).

78 Previous hydrogeochemical studies in the southern Yuncheng Basin have focused
79 mainly on shallow groundwater systems (Currell and Cartwright 2011; Li et al. 2015a;
80 Luo et al. 2018; Li et al. 2019b; Guo et al. 2026). For instance, Currell and Cartwright
81 (2011) combined groundwater, rainfall and sediment major-ion geochemistry with
82 $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{13}\text{C}$ data to investigate geochemical processes and sources of salinity in
83 groundwater, identifying evapotranspiration, carbonate weathering and cation
84 exchange as major contributors on groundwater salinity. Li et al. (2015b) analyzed 100
85 groundwater samples across the basin and revealed dissolution of fluorine-bearing
86 minerals and desorption of exchangeable fluoride in loess as the main sources of high
87 fluoride concentrations in groundwater. In previous studies, only a few geothermal
88 waters (1-3 samples) in the Salt Lake geothermal field have been analyzed, and these
89 analyses were limited to basic hydrochemistry (Li et al. 2026a) or to investigating the
90 relationship between geothermal water and fluoride/salinity enrichment in groundwater
91 (Li et al. 2019a). Few studies have integrated samples from more than a dozen deep
92 wells to characterize geothermal waters at depths greater than 2,000 m. The origin of
93 the exceptionally high salinity, which exceeds that reported for other sub-basins of
94 Fenwei Rift, also remains unresolved. Those gaps limit a comprehensive understanding

of this concealed geothermal system and its potential for exploration and sustainable utilization.

This study addresses these gaps through a comprehensive hydrogeochemical characterization of deep geothermal waters in the Salt Lake geothermal field. The objectives are to: (1) identify the water-rock interactions responsible for the unusually high salinity; (2) constrain the geothermal reservoir temperature by using appropriate geothermometers; (3) determine recharge sources and elevations; and (4) quantify the mixing process between deep thermal water and cold groundwater. The results enhance the understanding of fluid circulation, salinization, and the structural controls on geothermal exploration in this typical rift-basin system.

2 Geological setting

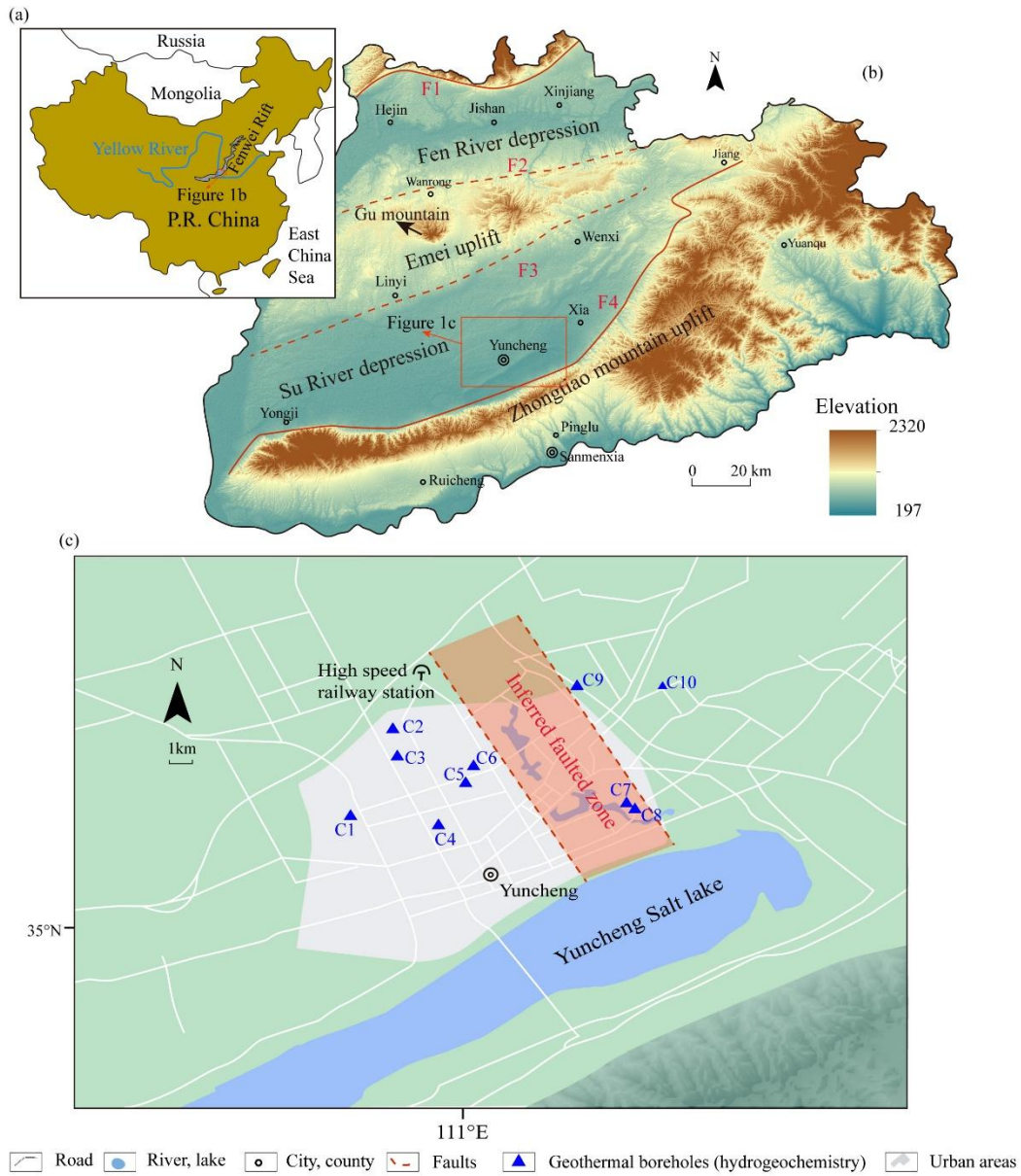


Fig. 1 (a) Location of the Yuncheng Basin; (b) Tectonic units of Yuncheng Basin overlaid on the elevation map; (c) Locations of geothermal fluid sampling boreholes in Salt Lake district, Yuncheng city. The inferred faulted zone is from Wu et al. (2025)

The Yuncheng Basin is situated in the southwestern part of the Cenozoic Fenwei Rift in northern China (see Fig. 1a). As illustrated in Fig. 1b, this basin is tectonically subdivided into three subunits: the Fen River Depression, the Emei Uplift, and the Su

113 River Depression, with NE-trending deep normal faults defining the boundaries
114 between these units. The major faults include the southern Lvliang margin fault (F1),
115 the northern Emei margin fault (F2), the southern Emei margin fault (F3), and the
116 northern Zhongtiao margin fault (F4) (Zhang et al. 2007; Su et al. 2023). The NW-
117 trending Wanrong-Dongguo fault (F5) crosses the main tectonic units and is likely
118 associated with deep granitoid intrusions in the Fen River Depression, a zone
119 characterized by moderate gravity and high magnetic values (Wu et al. 2026b). The
120 basement consists mainly of Archean-Proterozoic metamorphic rocks, including
121 gneisses and hornblendites, and quartzites, as well as Cambrian-Ordovician limestones.
122 Quaternary lacustrine clay, fluvial sand and gravel, and aeolian loess overlie the
123 basement and reach thicknesses of 300–500 m across the basin (Chen et al. 2021). Small
124 volumes of Mesozoic intermediate to felsic intrusions occur locally in the central and
125 southern basin (Qi et al. 2016; Ai et al. 2019).

126 The Su River Depression is an asymmetric, closed basin fill with Cenozoic
127 sediments that thicken southward to a maximum thickness of approximately 4,000 m
128 (Jin 2020). Mean annual rainfall is about 550 mm, whereas potential evapotranspiration
129 is around 2,000 mm per year. The climatic characteristic of evaporation far exceeding
130 precipitation, together with its enclosed topography, leads to the formation of the inland
131 salt lake, the Yuncheng Salt Lake (Zheng et al. 1993). Most precipitation occurs during
132 the East Asian summer monsoon can recharge the groundwater when rainfall exceed
133 evapotranspiration. Regional groundwater flow is predominantly from the northwest to

the southeast, broadly following the regional topography gradient, as evidenced by the constructed contour map (Currell and Cartwright 2011). Regarding geothermal potential, the Su River Depression holds two major geothermal fields: the Salt Lake geothermal field in the central-south area and the Linyi geothermal field in the north margin. The Linyi geothermal field, located in the recharge area, primarily hosts reservoirs composed of Cambrian-Ordovician limestones. In contrast, the Salt Lake geothermal field, situated in flow-through and discharge area, is characterized by thick sandstone-type thermal reservoirs, with geothermal gradients and temperatures exhibiting higher values in the southeast and lower values in the northwest (Wu et al. 2025). In terms of geothermal exploitation, the Salt Lake sandstone reservoir features high salinity and poor reinjection performance, whereas the Linyi well-karstified carbonate reservoir has low salinity and high yield (Li et al. 2026a).

3 Materials and methods

This study provides a systematic analysis of deep geothermal water from the concealed Salt Lake geothermal field. Ten water samples were collected primarily from geothermal wells with depths of approximately 2,000 m to 3,000 m. As illustrated in Fig. 1c, the sampling sites are spatially well-distributed across the geothermal field, including its western and eastern parts, which show contrasting subsurface temperature patterns (Wu et al. 2025). Major-ions and stable-isotopes sampling followed the relevant Chinese national standards. Most samples were analyzed at two ISO-certified laboratories in China: the Soil and Water Testing Centre of Shaanxi Engineering Survey

and Research Institute and the Groundwater, Mineral Water and Environmental Monitoring Center of the Ministry of Land and Resources. The analyses adhered to Chinese National Standards (GB/T) for drinking water and mineral water examination. The analyzed parameters include the major cations (K^+ , Na^+ , Ca^{2+} , and Mg^{2+}), the major anions (Cl^- , SO_4^{2-} , and HCO_3^-), and stable isotope analyses ($\delta^{18}O$). The ionic charge-balance error was less than $\pm 5\%$ for all samples, supporting the reliability of the analytical data.

Hydrochemical classifications and the processes controlling water chemistry were evaluated using Piper diagram (Piper 1944), Schoeller diagram (Yang et al. 2022; Li et al. 2026b) and Gibbs diagrams (Gibbs 1970), respectively. Major-ion molar ratios, including Na^+/Cl^- , Ca^{2+}/SO_4^{2-} , $(Ca^{2+}+Mg^{2+})/(HCO_3^-+SO_4^{2-})$, and $(Na^+ + K^+ - Cl^-)/[(Ca^{2+}+Mg^{2+})-(SO_4^{2-}+HCO_3^-)]$, were calculated to identify solute sources and assess the degree of water-rock interaction. To estimate the reservoir temperature, the Na-K-Mg ternary diagram was initially used to evaluate the water-rock equilibrium and the applicability of cation geothermometers (Giggenbach 1988). The SiO_2 -lg(K^2/Mg) diagram was employed to assess the equilibrium state of silica minerals (Powell and Cumming 2010). Saturation indices of relevant minerals were calculated using the geochemical modelling software PHREEQC (Parkhurst and Appelo 1999). The silica-enthalpy mixing model (Truesdell and Fournier 1977; Giori et al. 2017) were applied to quantify mixing between deep thermal and shallow cold waters and to reconstruct the original temperature of geothermal fluids prior to cold water mixing. Stable

hydrogen and oxygen isotopes (δD and $\delta^{18}O$) assist in identifying recharge sources and estimating its recharge elevation if sourced from meteoric water (Craig 1961).

4 Results and discussion

4.1 General hydrogeochemical characteristics

4.1.1 Water type analysis

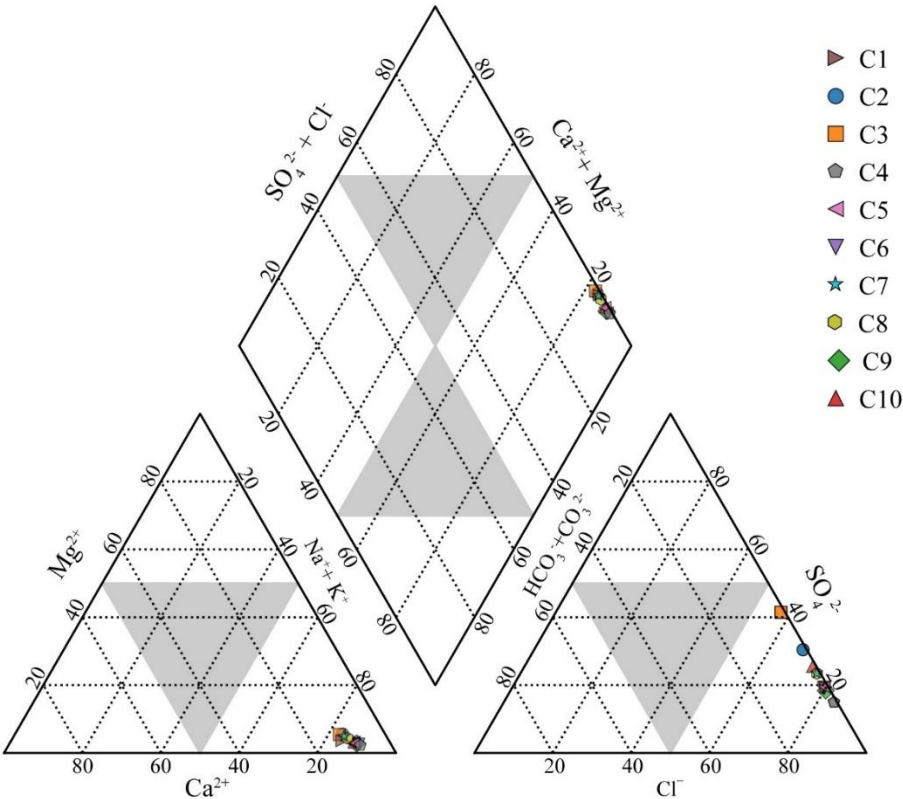


Fig. 2 The Piper diagram showing composition of geothermal water in the Salt Lake geothermal field

Table 1 Chemical parameters of geothermal fluid samples collected from the Salt Lake geothermal field

Sample ID	Wellhead temperature (°C)	pH	K ⁺ (mg/L)	Na ⁺ (mg/L)	Ca ²⁺ (mg/L)	Mg ²⁺ (mg/L)	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	HCO ₃ ⁻ (mg/L)	F ⁻ (mg/L)	TDS (mg/L)	SiO ₂ (mg/L)	δD (‰)	$\delta^{18}O$ (‰)
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C1	76	7.13	59.82	8147.0	1053.9	193.7	11908.7	3936.5	164.1	-	25729	52.39	-73	-8.2
C2	67	7.25	27.10	5279.0	601.2	186.9	6915.0	4156.0	167.5	1.70	17124	33.35	-75	-9.1
C3	79	7.89	33.93	5394.0	670.7	188.9	5699.5	5573.8	179.2	0.98	18064	52.39	-	-
C4	73	7.30	77.10	8101.2	631.3	109.4	11853.6	2857.8	195.3	1.05	23880	51.54	-	-
C5	81	7.93	59.98	6313.3	586.2	115.4	9128.4	3038.0	204.4	1.05	18712	40.23	-	-
C6	78	7.56	49.51	5990.0	481.7	93.6	8396.0	2748.0	215.1	1.50	18099	48.39	-74	-8.5
C7	64	7.64	45.90	5555.0	626.0	173.0	7533.0	3180.0	165.0	1.32	18096	47.00	-73	-8.6
C8	57	7.14	29.16	5457.0	570.8	148.7	7615.0	3200.0	155.6	-	17259	28.27	-74	-8.5
C9	65	7.96	75.90	5381.0	461.0	91.1	8605.0	2666.0	220.0	1.12	17580	44.69	-	-
C10	75	7.69	41.96	6495.0	590.8	125.9	8354.5	3925.6	191.8	-	19930	43.39	-	-

186 The concentrations of major cations and anions of the thermal water samples (C1-

187 C10) are listed in Table 1. The geothermal waters in the Salt Lake geothermal field are

188 slightly alkaline, with pH values of 7.13 to-7.96. The wellhead temperatures range from

189 64 °C to 81 °C, with an average of 72 °C. The total dissolved solids (TDS)

190 concentrations range from 17,124 mg/L to 25,729 mg/L, with a mean of 19,447 mg/L.

191 This average TDS content is significantly higher than those reported for most

192 geothermal waters in the Fenwei Graben and is nearly seven times that of the Xianyang

193 geothermal field (Average TDS value of 2,814 mg/L), which has similar Neogene and

194 Paleogene sandstone reservoirs and sedimentary thicknesses of up to 4,000 m (Liu et

195 al. 2024). It is inferred that, besides the intense water-rock interaction driven by the

196 extended groundwater flow path, other processes such as dissolution of evaporative

197 minerals or mixing with deep fluids may also contribute. In the Piper diagram (Fig. 2),

198 all the samples plot on the right side of the triangulars and in the central part of the

199 diamond field, indicating relatively uniform chemistry and a predominantly Cl-Na

200 hydrochemical facies.

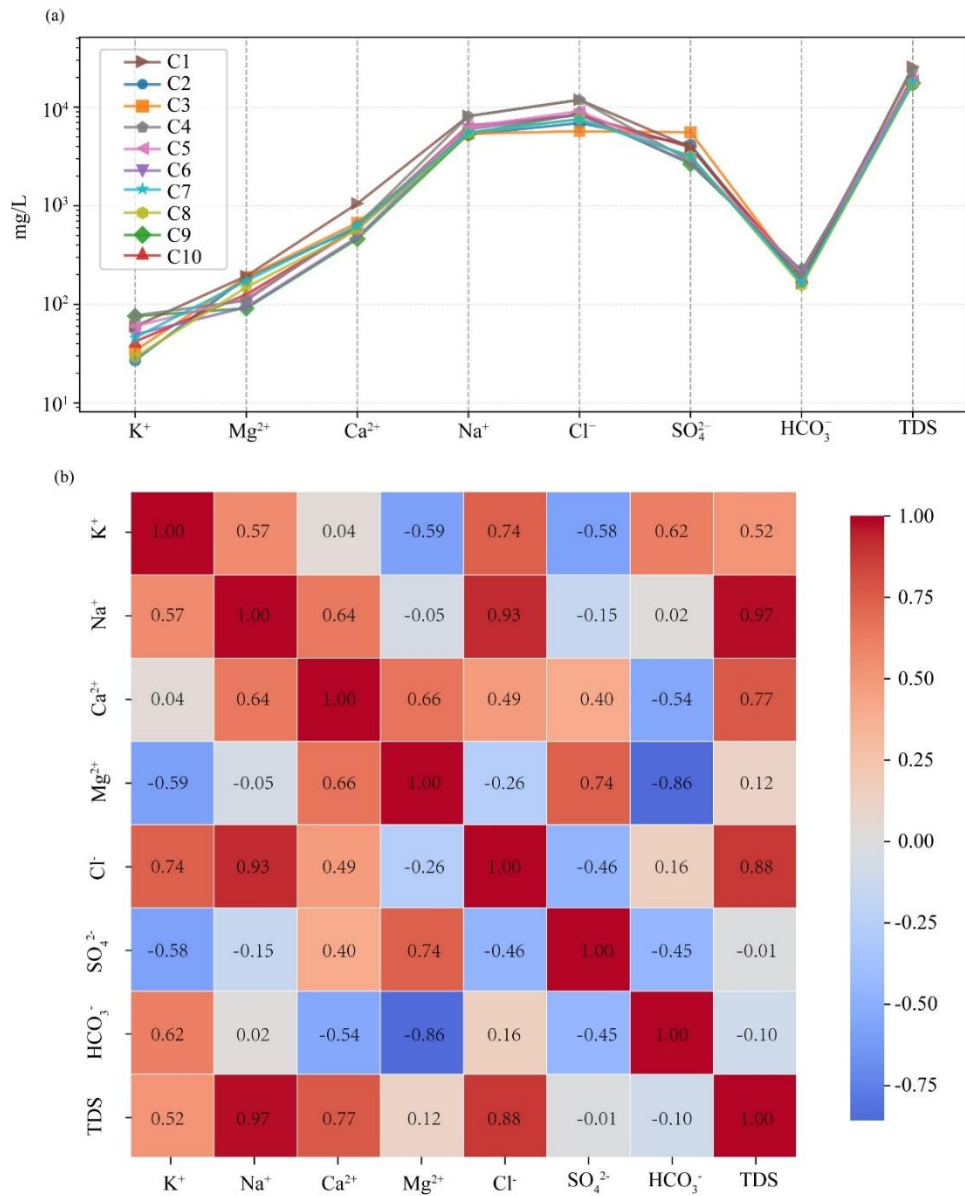


Fig. 3 (a) Schoeller diagram of water samples; (b) Pearson-correlation heatmap among different variables in the Salt Lake geothermal field

In the Schoeller diagram (Fig. 3a), the major ions (mg/L) in the geothermal waters are ranked as follows: $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ among cations, and $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-$ among anions. Na^+ is the dominant cation, reaching 8,147 mg/L, which is several times higher than those of the other major cations. Sulfate and chloride are the primary anions, with concentrations up to 5,573 mg/L and 11,908 mg/L, respectively. The coloration

diagram in Fig. 3b shows strong positive correlations between TDS and Cl^- , Na^+ , Ca^{2+} , and K^+ , with correlation coefficients (R^2) exceeding 0.70. This indicates these ions substantially contribute to total mineralization degree. The particularly strong TDS- Na^+ and TDS- Cl^- correlations highlight the role of sodium and chloride in the salinization of the geothermal water in this region.

4.1.2 Main source of dissolved ions

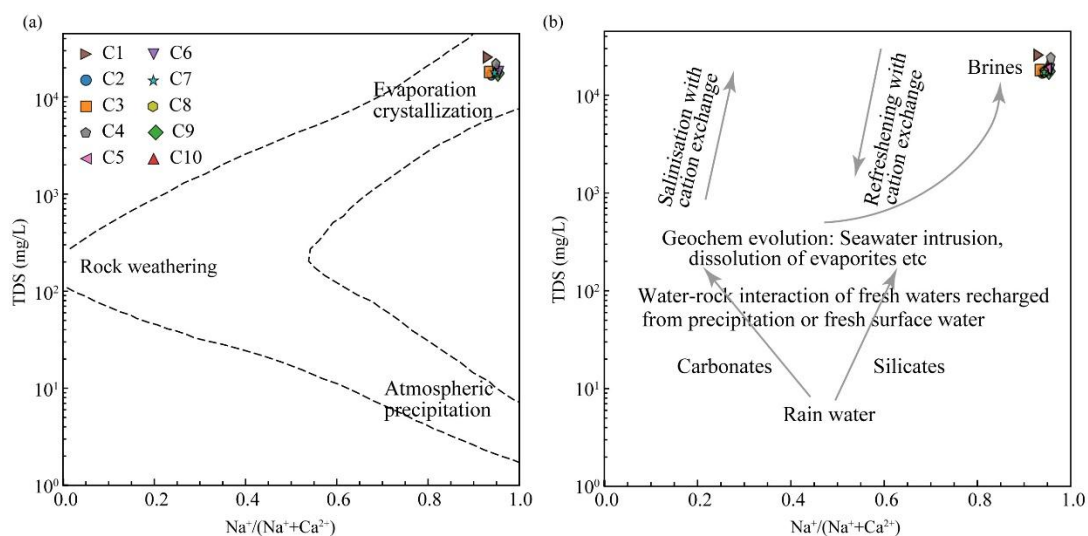


Fig. 4 Gibbs diagram for water samples in the Salt Lake geothermal field, with (a) illustrating the natural mechanisms governing surface water chemistry (Gibbs 1970) and (b) showing the extended application to groundwater systems (Marandi and Shand 2018)

By examining the evolution of surface water chemistry, Gibbs (1970) originally proposed three important natural mechanisms that control the major ion chemistry, including water-rock interaction, evaporation and atmospheric precipitation. In the Gibbs diagram, TDS concentrations are plotted against the weight ratios of $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ for cations and the weight ratios of $\text{Cl}^- / (\text{Cl}^- + \text{HCO}^-)$ for anions. As illustrated in Fig. 4a, most thermal water samples plot in the evaporation-dominant area, indicating

that evaporation significantly influences the chemistry of thermal waters. However, for deep geothermal waters, the impact of evaporation via water removal from deep aquifers is minimal, so a straightforward interpretation would be inappropriate (Barica 1972). Marandi and Shand (2018) argued that Gibbs plots involving groundwater systems should be reconsidered and reinterpreted within the broader hydrogeochemical context, as water-rock interactions can occupy most of the plot area, especially for groundwaters with residence times much longer than those typical of surface waters. They therefore proposed a modified Gibbs diagram specifically for groundwater systems, which are presented in Fig. 4b. The Salt Lake geothermal samples plotting in the upper-right part of groundwater Gibbs diagram (Fig. 4b) indicates that evaporite dissolution, rather than evaporation, is the more plausible explanation for the high salinity. Furthermore, the position of groundwater on either the left or right side of the modified Gibbs diagram depends on soil and aquifer properties. The Salt Lake geothermal water chemistry is shifted towards higher $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ ratios, suggesting that this geothermal system is dominated by silicates rather than carbonate minerals, consistent with sandstone reservoir.

Since the Gibbs Diagram considers only Na^+ and Ca^{2+} , it provides limited information about processes affecting Cl^- and SO_4^{2-} , including gypsum dissolution (Woldemariam and Ayenew 2016). Molar-ratio analyses were therefore employed to further reveal the dominant water-rock interaction processes and to identify the principal sources of major ions.

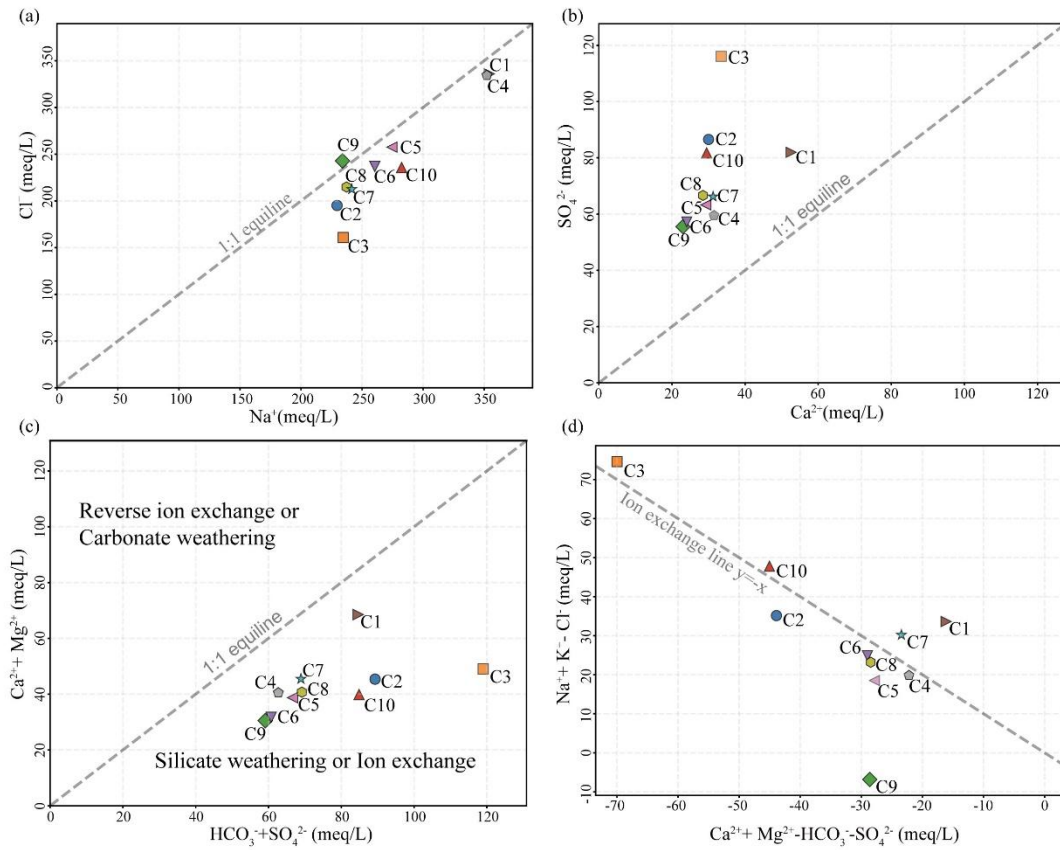


Fig. 5 Ion molar ratio diagrams for deep geothermal water in the Salt Lake geothermal field: (a) Na^+ vs. Cl^- , (b) Ca^{2+} vs. SO_4^{2-} , (c) $(\text{Ca}^{2+} + \text{Mg}^{2+})$ vs. $(\text{SO}_4^{2-} + \text{HCO}_3^-)$, and (d) $(\text{Na}^+ + \text{K}^+ - \text{Cl}^-)$ vs. $(\text{Ca}^{2+} + \text{Mg}^{2+} - \text{SO}_4^{2-} - \text{HCO}_3^-)$

The Na^+/Cl^- molar ratio helps identify sources of Na^+ . Most sample points lie below the Na-Cl line in Fig. 5a, with Na^+/Cl^- ratios greater than 1. This pattern indicates that the Salt Lake geothermal water contains excess Na^+ beyond that supplied by halite dissolution alone. Kou et al. (2024) reported the deep Paleogene Pinglu Group composed of arid lake deposits and gypsum layers may serve as a significant source of sodium, chloride, and sulfate. Therefore, the Na^+ in the deep geothermal water may originate from the dissolution of sodium-bearing minerals, including mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) and halite. In addition, cation exchange reactions, where Ca^{2+} or Mg^{2+}

in the water are adsorbed by clay minerals and Na^+ is released into solution, may also contribute to Na^+ enrichment.

The $\text{Ca}^{2+}/\text{SO}_4^{2-}$ molar ratio can help identify sources of Ca^{2+} and SO_4^{2-} . All samples plot above the 1:1 line in Fig. 5b, indicating that Ca^{2+} may be depleted due to ion adsorption (i.e., cation exchange). On the other hand, there may exist an additional source of sulfate, such as mirabilite dissolution.

The $(\text{Ca}^{2+} + \text{Mg}^{2+})/(\text{HCO}_3^- + \text{SO}_4^{2-})$ molar ratio is used to assess whether Ca^{2+} and Mg^{2+} are supplied by carbonate, silicate, or evaporite dissolution. As shown in Fig. 5c, all sample points lie below the 1:1 equiline, exhibiting a trend toward silicate weathering or cation exchange. This further suggests that Ca^{2+} and Mg^{2+} in the geothermal water may be adsorbed by clay minerals, resulting in the release of Na^+ .

The $(\text{Na}^+ + \text{K}^+ - \text{Cl}^-)/[(\text{Ca}^{2+} + \text{Mg}^{2+}) - (\text{SO}_4^{2-} + \text{HCO}_3^-)]$ molar ratio provides an additional indicator of cation exchange in the geothermal water. The negative correlation in Fig. 5d suggests that Na^+ has undergone cation exchange with Ca^{2+} and Mg^{2+} . This process leads to an increase in Na^+ concentration and a corresponding depletion in Ca^{2+} and Mg^{2+} concentrations in the aqueous medium of the study area. Extensive cation exchange has also been reported in the shallow Quaternary aquifer of the Su River Depression (Currell and Cartwright 2011).

The water type and molar-ratio results indicate that the Salt Lake geothermal water interacts with clay-rich, silicate-dominated reservoirs at depth and undergo widespread cation exchange processes. However, cation exchange alone cannot explain the

exceptionally high TDS observed. The study of shallow groundwater in Yucheng Basin by Luo et al. (2018) provides a useful regional comparison. In the central discharge areas of the Yuncheng Basin, shallow groundwater reached a maximum TDS concentration of 17,452 mg/L and was dominated by Na^+ , with SO_4^{2-} and/or Cl^- as the principal anions. These values are comparable to, although slightly lower than, the mean TDS concentration of 19,447 mg/L measured in the deep geothermal waters of the Salt Lake field. The similar Na-rich and sulfate/chloride-rich chemistry, together with the reported distribution of halite, gypsum, and mirabilite in the basin sediments, suggests that evaporite dissolution is a regional control on salinization across both shallow and deep groundwater systems. The comparison therefore supports a common evaporite source for dissolved salts. Therefore, dissolution of halite and mirabilite minerals during the deep water migration along deep-seated faults is inferred to be a major contributor to the high salinity of the Salt Lake geothermal field.

4.2 Geothermal temperature estimation and cold-water mixing

4.2.1 Water-rock equilibrium state

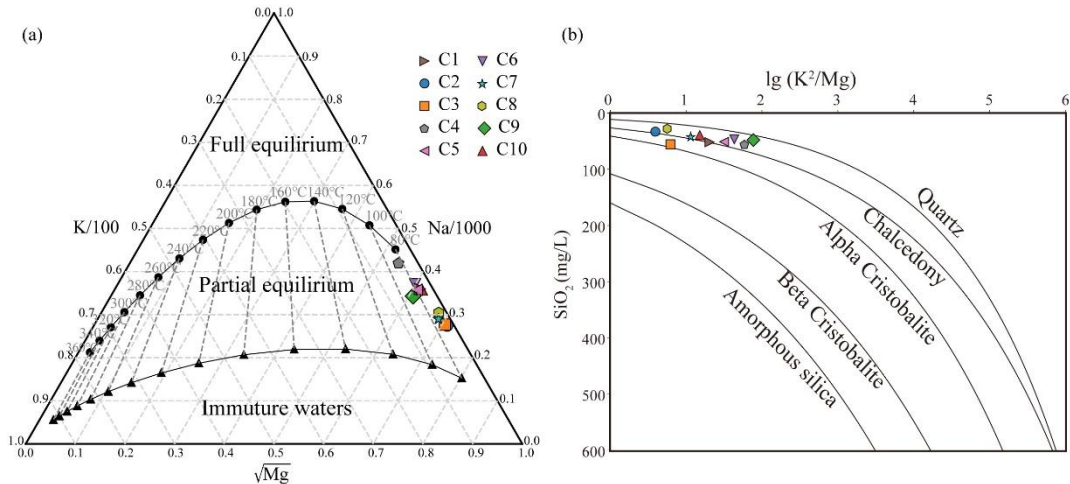


Fig. 6 (a) Na-K-Mg ternary diagram; (b) SiO_2 -lg (K^2/Mg) relationship diagram for deep geothermal water samples in the Salt Lake geothermal field

Based on the relative abundance of Na, K and Mg, the Na-K-Mg ternary diagram is widely used to classify geothermal waters as fully equilibrated with rocks at given temperatures, partially equilibrated, or immature (Giggenbach 1988). This diagram also provides insights into the applicability of cation geothermometers. As shown in Fig. 6a, all the thermal water samples in the Salt Lake geothermal field fall within the partially equilibrated field, indicating that geothermal fluids did not reach complete chemical equilibrium with the surrounding reservoir rocks or were subsequently modified by mixing with shallow cold water. Therefore, Na-K and Na-K-Ca geothermometers were consequently not considered reliable for direct reservoir-temperature estimation. Moreover, it can be also observed in Fig. 6a that the thermal water samples display a linear distribution trend along the 80 °C equilibrium line, suggesting these samples may have evolved from a common parent geothermal fluid.

4.2.2 Mineral Equilibrium State

Mineral equilibrium calculations by the saturation indices (SI) of relevant minerals in the geothermal water can help further evaluate the equilibrium state and identify the potential minerals involved in water-rock interaction (Parkhurst and Appelo 1999). The calculation formula is as follows:

$$\text{SI} = \lg(Q / K) \quad (1)$$

Where K represents the minerals solubility in geothermal water (mol/L), and Q is the actual ion activity product of minerals dissolved in the solution (mol/L). Positive SI

value indicates supersaturation and a tendency towards mineral precipitation, whereas negative value means unsaturation and a potential for continued dissolution. An SI of zero represents equilibrium between the mineral and the geothermal water.

Table 2 Calculated saturation index (SI) of different minerals for thermal water samples from the Salt Lake geothermal field

Sample ID	Dolomite	Calcite	Aragonite	Quartz	Chalcedony	Anhydrite	Gypsum	Fluorite	Halite	Mirabilite
C1	1.34	0.86	0.75	0.34	0.05	0.22	0.03	-	-2.97	-4.58
C2	1.26	0.69	0.57	0.22	-0.09	0.00	-0.10	-0.93	-3.35	-4.46
C3	2.37	1.34	1.23	0.26	-0.02	0.28	0.06	-1.48	-3.46	-4.76
C4	1.40	0.88	0.77	0.36	0.06	-0.12	-0.28	-1.37	-2.96	-4.56
C5	2.44	1.42	1.31	0.13	-0.15	0.03	-0.22	-1.43	-3.19	-4.98
C6	1.84	1.11	1.00	0.26	-0.03	-0.10	-0.32	-1.14	-3.23	-4.93
C7	1.96	1.04	0.92	0.40	0.08	-0.12	-0.18	-1.09	-3.28	-4.42
C8	0.80	0.46	0.34	0.27	-0.07	-0.21	-0.21	-	-3.26	-4.15
C9	2.37	1.32	1.20	0.35	0.03	-0.28	-0.35	-1.31	-3.24	-4.53
C10	2.02	1.17	1.06	0.24	-0.05	0.04	-0.14	-	-3.20	-4.63

In this study, the multiminerale SI values were computed using PHREEQC 3.0 software. The selected input parameters in this study include wellhead temperature, pH, Na⁺, K⁺, Mg²⁺, Ca²⁺, Cl⁻, SO₄²⁻, HCO₃⁻, and Si. The calculation results are summarized in Table 2. Gypsum, anhydrite, and chalcedony are close to equilibrium, with SI values around zero, whereas quartz is slightly supersaturated (SI = 0.13 to 0.40), indicating that quartz may also influence the dissolved SiO₂ concentrations. Calcite, dolomite, and aragonite are supersaturated (SI > 0), indicating a potential tendency for carbonate-mineral precipitation during geothermal-fluid evolution. In contrast, halite and fluorite are undersaturated (SI < 0). The undersaturation of halite suggests that the sampled waters are not in equilibrium with halite at measured conditions and may continue to dissolve halite if halite-bearing formations occur at depth. This provides additional

support for the contribution of evaporite dissolution to the high salinity of the geothermal fluids.

4.2.3 Silica geothermometer

Based on the mineral saturation-index results for quartz and chalcedony, silica geothermometers were then applied to provide a preliminary constraint on the thermal conditions of the sampled fluids. As shown in Fig. 6b, most borehole samples plot between the quartz and chalcedony equilibrium curves on the $\text{SiO}_2\text{-lg}(\text{K}^2/\text{Mg})$ diagram, suggesting that the dissolved silica in the geothermal water may have been controlled by both minerals. The relevant formulas for the quartz and chalcedony geothermometers employed in this study are given below:

Quartz temperature scale (no vapor loss)

$$T \text{ (}^\circ\text{C)} = 1309 / (5.19 - \lg \text{SiO}_2) - 273.15 \quad (2)$$

Chalcedony temperature scale (no vapor loss):

$$T \text{ (}^\circ\text{C)} = 1032 / (4.69 - \lg \text{SiO}_2) - 273.15 \quad (3)$$

Table 3 Estimated reservoirs temperatures ($^\circ\text{C}$) for thermal water samples from the Salt Lake geothermal field

Sample ID	Quartz (no vapour loss)/ $^\circ\text{C}$	Chalcedony (no vapour loss)/ $^\circ\text{C}$	Silicon enthalpy equation / $^\circ\text{C}$
C1	104.00	74.23	142.60
C2	83.82	52.72	112.56
C3	104.00	74.23	137.45
C4	103.23	73.41	146.36
C5	91.94	61.33	107.73
C6	100.30	70.25	130.83
C7	98.952	68.81	155.15
C8	76.98	45.50	117.26
C9	96.65	66.35	147.17

The calculated results are summarized in Table 3. The temperatures estimated using the quartz geothermometer range from 76.98 °C to 104.00 °C, whereas those estimated using the chalcedony geothermometer range from 45.00 to 74.00 °C. The temperature maps interpolated from borehole temperature logs show that the temperature varies from 59.89 °C to 90.45 °C at 2,000 m depth and from 65.62 °C to 117.53 °C at 3,000 m depth (Wu et al. 2025). By comparison, the quartz-geothermometer estimates are more consistent with the average temperatures derived from the borehole logs between 2,000 m and 3,000 m than the chalcedony geothermometer estimates. In contrast, the chalcedony-geothermometer estimates are comparable to the measured wellhead temperatures but are largely lower than the temperatures indicated by the borehole logs. The sampled borehole waters in this study represent mixed fluids that may have originated from different stratigraphic units and may have been diluted by shallow cold groundwater during ascent. Such mixing lowers the dissolved SiO₂ concentration and consequently underestimates the temperature of the deep parent fluid.

4.2.4 Silica-enthalpy mixing model

To quantify the cold-water mixing effect, the silica-enthalpy mixing model was employed to estimate the fraction of shallow cold water and the temperatures of the deep geothermal end member (Truesdell and Fournier 1977; Giriarso et al. 2017; Cao

et al. 2023; Huang et al. 2026). The silica–enthalpy mixing model was calculated using Eqs. (4) and (5):

$$H_c X + H_h (1 - X) = H_m \quad (4)$$

$$Si_c X + Si_h (1 - X) = Si_m \quad (5)$$

where H_c is the enthalpy of the shallow cold water (J/g), H_h is the enthalpy of the deep geothermal water (J/g), and H_m is the enthalpy of the geothermal water collected from the borehole (J/g). Si_c , Si_h , and Si_m denote the concentrations of dissolved SiO_2 in the cold water, deep geothermal water, and borehole geothermal water, respectively (mg/L). X represents the proportion of cold water in the mixed geothermal fluid. The deep-end-member silica concentration and enthalpy were determined from the silica–enthalpy relationship used in the model. Based on the data reported by Li et al. (2015a), the shallow cold groundwater in the Yuncheng Basin was assigned a temperature of 18 °C and a SiO_2 concentration of 2.2 mg/L.

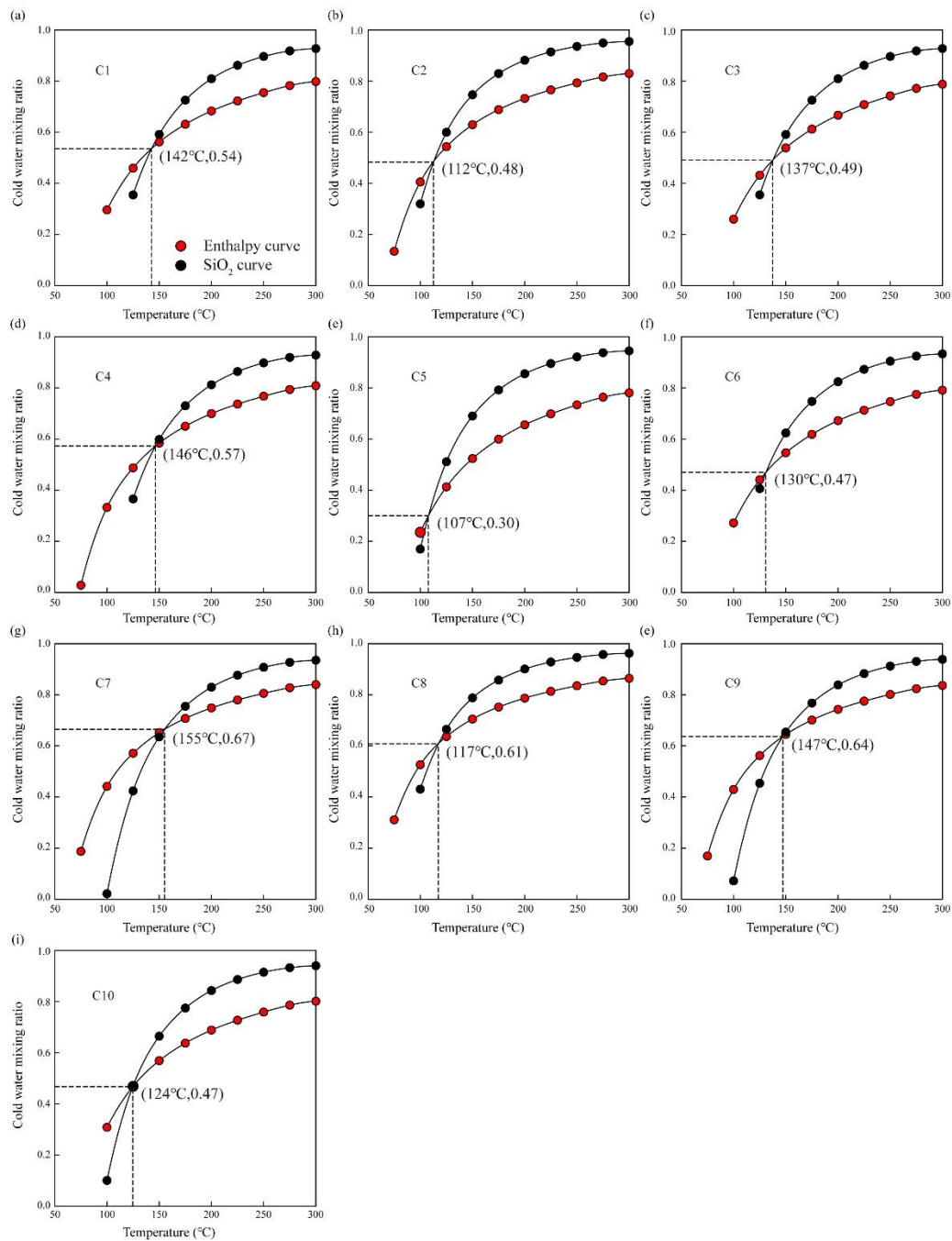


Fig. 7 Silicon-enthalpy mixing diagrams for deep geothermal water samples in the Salt Lake geothermal field

As shown in Fig. 7, the cold-water ratio and the temperature prior to cold water mixing were obtained in silicon-enthalpy mixing model. The calculated proportion of shallow cold water ranges from 30 % to 67 %. Samples C7-C9 show the highest mixing

ratio of shallow cold water (all larger than 60%) and are located within and/or near the inferred fractured zone shown in Fig. 1c. The original temperature of the deep geothermal end member is between 107 °C and 155 °C, substantially exceeding both the measured wellhead temperatures and the temperatures obtained from the SiO₂ geothermometers. This difference confirms that the latter were lowered by cold-water dilution and conductive cooling during fluid ascent.

The spatial distribution of the mixing proportions provides important evidence for the hydraulic role of the fractured zone. In particular, the relatively high cold-water ratio in samples C7–C9 suggests that the fractured zone acts as a preferential conduit for the downward penetration of shallow groundwater into the deeper geothermal system. The resulting cold-water influx reduces the temperature of the mixed geothermal fluids and modifies their dissolved chemical composition. Therefore, the silica-enthalpy results further provide a hydrogeochemical explanation for the lower subsurface-temperature anomalies observed in the eastern part of study area reported by Wu et al. (2025).

The combined results of the water–rock equilibrium assessment, mineral saturation-index calculations, silica geothermometers, and silica–enthalpy modeling indicate that the Salt Lake geothermal field is a deep, low- to medium-temperature geothermal system. The wellhead temperatures and SiO₂-geothermometer temperatures provide lower-temperature constraints, whereas the silica–enthalpy model yields higher temperature estimates of 107–155 °C for the deep geothermal end member. Shallow

cold-water mixing has extensively modified the geothermal fluids, particularly near the concealed fractured zone in the eastern part of the study area.

4.3 H-O isotope geochemistry

4.3.1 Geothermal water recharge origin

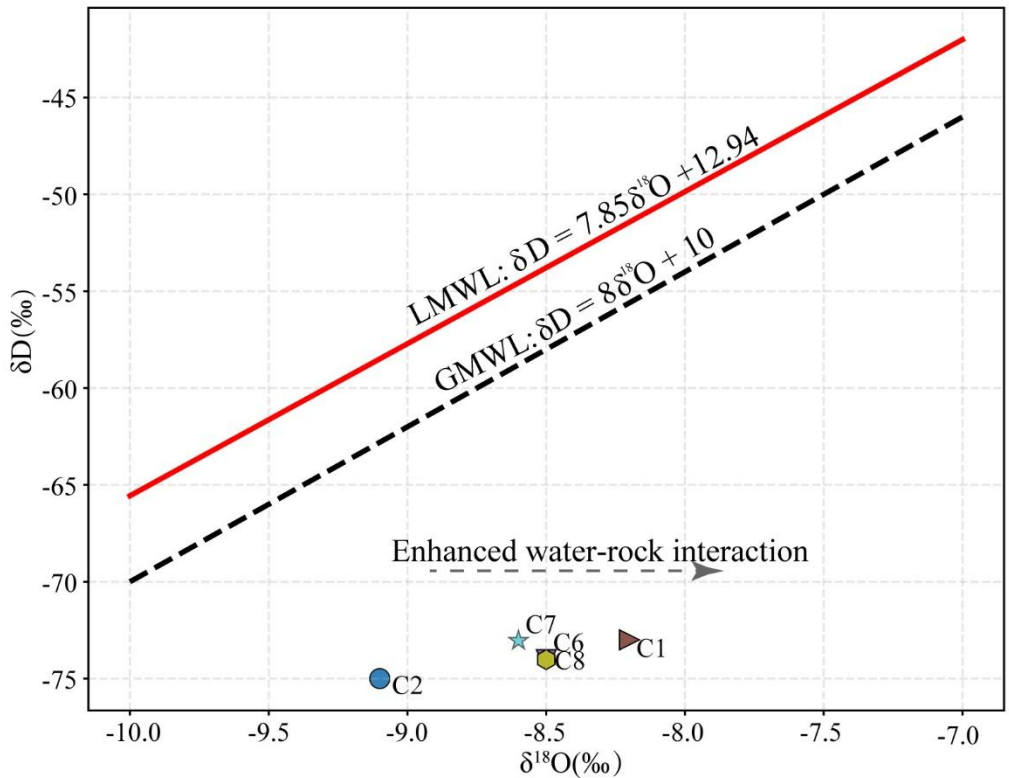


Fig. 8 δD – $\delta^{18}O$ relationships of deep geothermal water samples in the Salt Lake geothermal field

Stable hydrogen and oxygen isotopes (δD and $\delta^{18}O$) have been demonstrated to serve as reliable tracers for determining the recharge origin of geothermal water (Chang et al. 2021; Liu et al. 2024; Yan et al. 2024; Yuan et al. 2025). In this study, the Global Meteoric Water Line (GMWL: $\delta D = 8\delta^{18}O + 10$; Craig 1961) and the Local Meteoric Water Line (LMWL: $\delta D = 7\delta^{18}O + 4.8$; Li et al. 2015a) were used as reference lines. As depicted in the δD versus $\delta^{18}O$ diagram (Fig. 8), the five geothermal water samples

(C1, C2, C6, C7, and C8) with available isotope data plot near both the GMWL and LMWL, indicating a meteoric origin. Their $\delta^{18}\text{O}$ values are shifted significantly to the right of both the GMWL and LMWL, implying extensive water-rock interaction, during which circulating waters preferentially incorporate ^{18}O from the surrounding reservoir rocks. A comparison of geothermal waters between Xianyang (Liu et al. 2024) and Yuncheng reveals similar degrees of oxygen isotope enrichment ($\delta^{18}\text{O}$), suggesting comparable degrees of water-rock interaction.

This finding further supports the interpretation that the elevated salinity observed in the Salt Lake geothermal water is primarily attributable to the dissolution of deep-seated salt-bearing mineral layers, in addition to intense water-rock interaction.

4.3.2 Geothermal water recharge elevation

The δD and $\delta^{18}\text{O}$ values have been widely used to estimate recharge elevation because precipitation becomes isotopically lighter with increasing altitude. As shown in Fig. 8, all geothermal water samples are enriched in $\delta^{18}\text{O}$, exhibiting a positive isotopic shift relative to both the GMWL and LMWL. This indicates the presence of the “ $\delta^{18}\text{O}$ -shift” phenomenon, which makes $\delta^{18}\text{O}$ unsuitable for recharge elevation estimation. Since rocks are generally poor in hydrogen, water–rock interactions generally produce no measurable shift in δD (Giggenbach 1992). Therefore, δD was selected as the more reliable tracer for estimating the recharge elevation in this study.

The formula used for elevation calculation is as follows:

$$H = h + (\delta G - \delta p)/K \quad (6)$$

Where H represents the recharge elevation (m), h denotes the elevation of the sampling point (m), δG is the δD value in the geothermal water sample, δP is the δD value of surface water, and K is the δD elevation gradient of atmospheric precipitation. Based on previous studies (Ma et al. 2006), the K value is -2.50 ‰/100 m. The δP value is -59.1 ‰, and the surface water sample elevation (h) of 340 m (Luo et al. 2018). The estimated recharge elevations of the Salt Lake geothermal water ranges from 893.78 m to 973.47 m, with an average of 925.66 m. Considering the topography, geomorphology, and structural characteristics of the basin, direct recharge from the surface Yuncheng Salt Lake is unlikely, which support the absence of a direct hydraulic connection between the Yuncheng Salt Lake and the deep geothermal reservoirs proposed by (Wu et al. 2025). Instead, the estimated elevation is compatible with recharge from the surrounding Zhongtiao Mountain and Gu Mountain.

The recharge source and elevation estimate therefore indicate that the geothermal waters are primarily recharged by meteoric precipitation infiltrating through Gu Mountain to the north and Zhongtiao Mountain to the south.

5 Conceptual model of the Salt Lake geothermal system

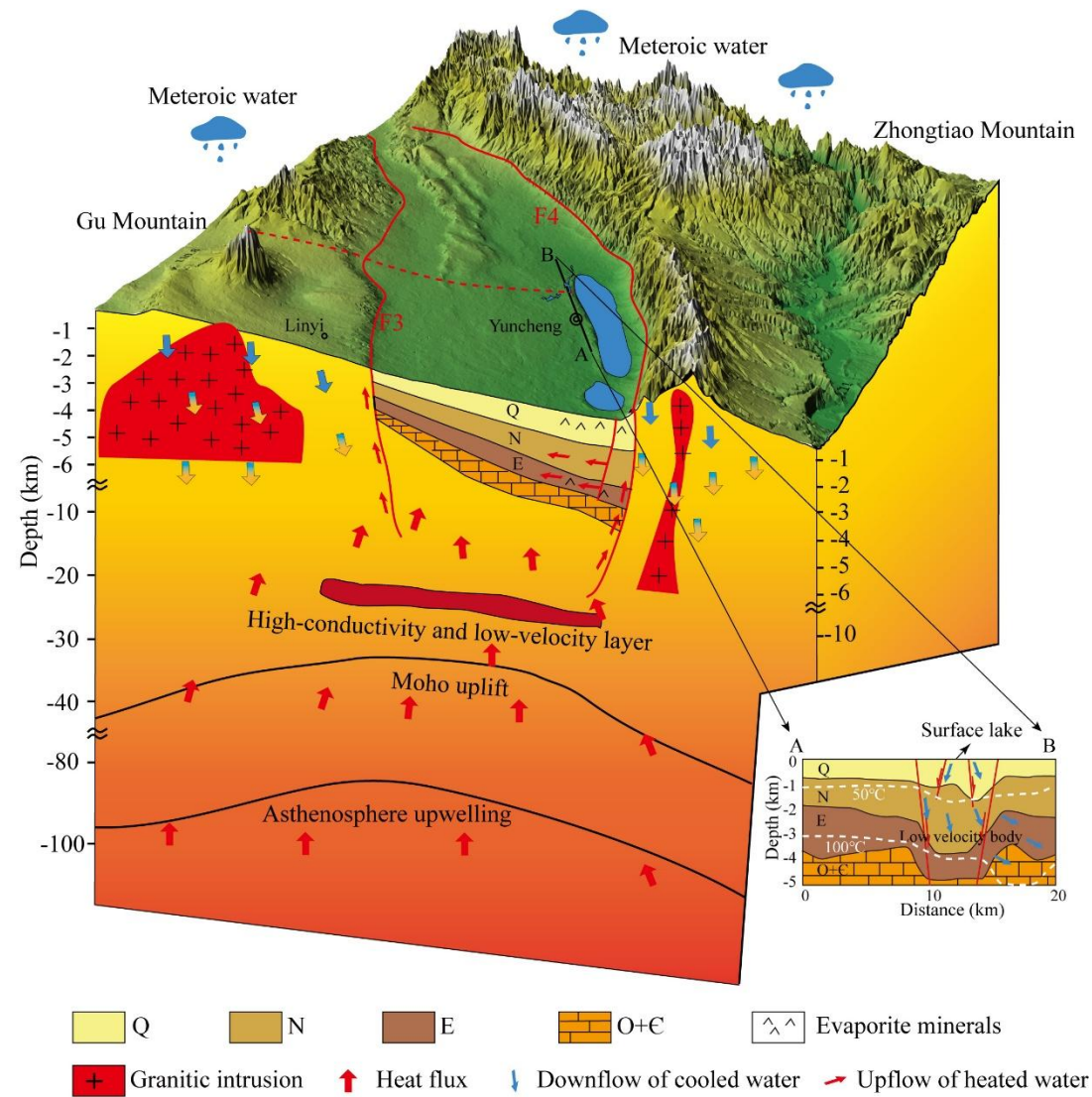


Fig. 9 Conceptual model of the geothermal system in the Salt Lake geothermal field, Yuncheng basin. The deep stratigraphic configuration and temperature isotherms along the profile A-B are adapted from Wu et al. (2025)

By integrating the topographic and geological setting, previous numerical modelling (Wu et al. 2025; Wu et al. 2026a), and the hydrochemical results from this

study, a revised conceptual model of the Salt Lake geothermal system is proposed (Fig. 9). This model further refines the sources of salinity and the shallow cold water mixing processes in the eastern part of the field.

The geothermal water in the Salt Lake geothermal field is primarily recharged by meteoric precipitation from the northern Gu Mountain and the southern Zhongtiao Mountain. Driven by topographical gradients, the infiltrating water migrates vertically downward along the sloping southern and northern margins, especially the southern Emei margin fault and Zhongtiao margin fault, ultimately converging toward the central-southern areas of the Su River subbasin. During deep circulation through the sandstone reservoirs beneath the Salt Lake geothermal field, the geothermal groundwater undergoes prolonged water-rock interaction, ion exchange, as well as the potential dissolution of thin evaporite layers and/or lenses such as gypsum, halite and mirabilite. These processes collectively lead to the formation of the unique high-salinity geothermal water in this region. Meanwhile, the fluids keep absorbing heat at depth in the tectonically rift setting, where asthenosphere upwelling, lithospheric thinning and potential partial melting may contribute to the regional thermal regime (Xu and Ma 1992; Yin et al. 2017; Chen et al. 2021). The thick Quaternary sedimentary sequence acts as an effective caprock and inhibit heat loss. The deep heated fluids ascend along the permeable pathways, including the northern Zhongtiao basin-controlling extensional fault, to the near deep reservoirs. The active segments adjacent to the Salt Lake geothermal field may enhance permeability and serve as a favorable conduit for

subsurface fluids ascent (Cheng and Yang 2002; Jin 2020; Fronzi et al. 2021). The Salt Lake geothermal field is therefore a medium- and low-temperature extensional system. It should be also noted that deep geothermal water may have undergone extensive influence from shallow cold groundwater near the concealed NW-trending faults in the eastern part of the study area, thereby lowering reservoir temperatures and reducing the geothermal potential in this eastern region.

6 Conclusions

This study presents a comprehensive hydrogeochemical investigation of the deep geothermal fluids in the concealed Salt Lake geothermal field. The main conclusions are drawn as follows:

(1) The geothermal waters are predominantly of the Cl-Na type, with an average TDS of approximately 19,447 mg/L, significantly higher than any previously reported value for other sub-basins of the Fenwei Rift. Gibbs diagrams and molar ratios analyses suggest that dissolution of halite and sodium-sulfate evaporites, together with cation exchange and silicate interaction, contribute to the high salinity.

(2) Stable isotopes (δD and $\delta^{18}O$) indicate a meteoric origin with extensive water rock interaction and pronounced $\delta^{18}O$ enrichment. Estimated recharge elevations of 893.78–973.47 m are consistent with recharge from the northern Gu Mountain and southern Zhongtiao Mountain. Direct charge from Yuncheng Salt Lake is unlikely.

(3) The quartz and chalcedony geothermometers yield temperatures of 76.98–104.00 °C and 45.00–74.00 °C, respectively. Because the sampled waters are mixed

fluids, these values are treated as preliminary indicators rather than definitive reservoir temperatures. The silica–enthalpy model indicates 30%–67% mixing with shallow cold water, with contributions exceeding 60% in samples C7–C9 near the concealed NW-trending fractured zone. The reconstructed temperature of the deep geothermal end member is 107–155 °C, indicating structural control of local cooling.

(4) The Salt Lake geothermal field is an extensional geothermal system in the Basin and Range structural setting. Thick Quaternary sediments act as a caprock, while the active Zhongtiao margin fault facilitates fluid ascent. Meteoric recharge from Gu Mountain and Zhongtiao Mountain undergoes deep circulation, water–rock interaction, cation exchange, and evaporite dissolution in thick Paleogene–Neogene strata.

(5) The number of deep borehole samples is still limited ($n = 10$), providing an initial geochemical baseline for this concealed system. Additional sampling in the Salt Lake and Linyi geothermal fields is needed to refine the water-rock interaction and salinization pathways.

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