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Research Paper

Distribution and enrichment of potassium and lithium in Qaidam Basin brine, China*

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Abstract Qaidam Basin, located in the northeastern Qinghai-Xizang Plateau with high-mountain and deep-valley tectonic setting, is rich in mineral resources of many critical elements of mainly potassium (K), lithium (Li), magnesium (Mg), sodium (Na), uranium (U), and boron (B) leading the nation in these categories. To clarify the distribution and enrichment of potassium and lithium in Qaidam Basin brine, hydrochemical analyses and phase diagrams were carried out on brine water, salt spring water, and inflow river water. Results reveal that paleo-lake water migrated from the northwest to the Triple-lake region in an inverted S-shaped pattern under the control of gravitation. Due to the chemical differentiation, K shows an enrichment trend along the migration path from the northwest to the Triple-lake region, whereas Li is predominantly concentrated in East Taijinar (Dongtai), West Taijinar (Xitai) Lake, and Bieletan mining section in the lower catchments of Nalingele River. The Cl-SO_4 type of brines are widely distributed along the migration pathway. However, river water influx has shifted the hydrochemical type of Dongtai and Xitai lakes and Bieletan section into Na-HCO_3-SO_4 type. Salt spring that distributed along faults contribute a large amount of Ca, K, and Mg elements, thus turn water into Ca-Cl type. Glacial meltwater, after leaching granite and other rock, serves as the primary source of K, and Ca-Cl-typed salt springs are the significant source of both K and Li. These springs have modified the brine chemistry compositions and increased K and Li concentrations in Mahai Lake, Qarhan Salt Lake, and Dalangtan Salt Lake. This systematic analysis of K and Li distribution and enrichment mechanisms provides critical insights for the sustainable exploitation of brine resources in the Qaidam Basin.

Keyword: Qaidam Basin; brine; potassium; lithium; salt spring

1 INTRODUCTION

Salt lakes, as terminal evaporative basins in arid regions, represent a unique hydrogeochemical system formed by multi-sphere interactions, such as hydrosphere, atmosphere, lithosphere and biosphere. Their genesis fundamentally stems from a prolonged imbalance between evaporative loss and hydrological recharge, leading to progressive brine concentration with total dissolved solids exceeding 50 g/L (Zheng et al., 1989, 2016; Zheng, 2001). Under intense evaporative forcing, ionic concentration processes drive the geochemical enrichment of economically critical elements (K, Li, B, Rb, Cs, U) within residual brines through fractional crystallization and solute fractionation mechanisms. China’s continental interior hosts over a thousand documented salt lakes across various tectonic and climatic regimes, constituting a strategic repository of lithium-rich brine resources with significant metallogenic potential (Zheng et al., 1993, 2002; Qian, 1994; Zheng, 2001; Yan et al., 2016).

The Qaidam Basin, located in the northeastern

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part of the Qinghai-Xizang Plateau, has developed a distinctive "high-mountain-deep-basin" geomorphology in its northwestern region due to the influence of the Himalayan orogeny, which triggered the successive uplift of surrounding mountain ranges such as the Kunlun Mountains, Altun Mountains, and Qilian Mountains. Glacial meltwater is the primary medium for transporting K and Li in the brine systems of the Qaidam Basin's salt lakes (Zhang, 1987; Zheng et al., 1989; Fan et al., 2018; Li, 2022a; Han et al., 2024), providing perfect tectonic environments for K and Li deposits (Yang and Zhang, 1996; Han, 2008; Du, 2018; Ren, 2021). Regarding the genetic theories of potash deposits in the Qaidam Basin, Zheng et al. (2013, 2016), Chen and Bowler (1985), and Chen et al. (1990) proposed that the western Qaidam Basin was originally occupied by a unified paleolake during its early evolutionary stage. This ancestral lake became fragmented through multiple phases of tectonic activity, leading to brine migration and subsequent multistage concentration for mineralization. In contrast, Zhu et al. (1990, 1994) argued for the existence of a series of discrete paleolakes in the east Kunlun region. These paleolakes were disrupted by neotectonic movements and subsequently captured by fluvial systems, with their brines gravitationally transported to topographical depressions such as the Qarhan Playa where they underwent evaporative concentration. Alternatively, Lowenstein et al. (1989), Fan et al. (2018), and Zhang et al. (1991) postulated that the modern brines in the Qaidam Basin salt lakes was formed through mixing between riverine waters and Ca-Cl type brines in varying proportions. Meanwhile, studies further reveal that the Gasikule Salt Lake and Dalangtan Salt Lake in the western Qaidam Basin were formed through the dissolution and leaching of paleo-salt deposits by glacial meltwater, resulting in significant enrichment of metallogenic materials (Wang and Ye, 1992; Yuan et al., 1995; Ge and Cai, 2001; Li et al., 2022a, b; Zhang et al., 2024). The abundant oil and gas resources surrounding the Kunteyi Lake have made oilfield brine one of the significant recharge sources for the Kunteyi saline lake (Ai, 2018; Fan et al., 2018; Li, 2018; Li et al., 2021a). The incorporation of spring water from the Bukadaban Peak into the Nalinggele River in the central-eastern Qaidam Basin results in significantly higher lithium concentrations in the river water compared to other rivers in the basin (Yu et al., 2013; Li et al., 2019, 2021b; Li, 2020, 2022b; Rao et al., 2025). Some other efforts have been made on the minerals and evolution of Qaidam Basin (Zhu et al., 1989, 1994; Chen et al., 2020; Song et al., 2024; Zhong et al., 2024; Zhang et al., 2025).

Although numerous studies have been conducted on the brines of Qaidam Basin, most focused on individual salt lakes, with limited systematic research on the distribution and enrichment mechanisms of K and Li across the entire basin. Based on collected water sample data and published datasets, this study employs interpolation methods and hydrogeochemical modeling to investigate the spatial patterns and controlling factors of K and Li in the basin brines.

2 GEOLOGICAL SETTING

Qaidam Basin, located in the northeastern Qinghai-Xizang Plateau, is one of the largest inner continental basins in China. Its unique tectonic setting with high-mountain, deep-valley, and extreme continental climate have facilitated the formation of abundant metallic and non-metallic mineral deposits (Zhang, 1987; Wang et al., 2013; Zhu et al., 2017; Abudukeyumu et al., 2022; Zhang et al., 2022a; Pan et al., 2023), earning the reputation as "Treasure Basin".

Multi-phase thrusting events triggered a large-scale marine regression in the Tarim region in late Permian, causing the Tarim Basin to disengage from the Tethys Sea and transition into a paralic environment (Zhang, 1987; Li, 2022a). By the Early Jurassic, the integrated uplift of the Kunlun and Altun Mountains led to the complete shift of the Qaidam Basin to a continental depositional setting, accompanied by the formation of multiple fault-bound depressions. N-S directed compression resulting from the India-Eurasia collision maintained persistent regional stress fields across the Qinghai-Xizang Plateau in late Mesozoic. Concurrent activation of the Kunlun and Altun strike-slip fault systems induced extensional deformation and large-scale uplift within the Qaidam Basin (Zhu et al., 1994; Wang, 2020; Ren, 2021) (Fig.1). The uplift of surrounding mountains established glacial meltwater as the primary water source for the basins. Meanwhile, the sustained uplift of the Qinghai-Xizang Plateau intensified aridification across Central Asia (Thunell and Belyea, 1982; Raymo and Ruddiman, 1992; Dwyer et al., 1995). This was further exacerbated by the

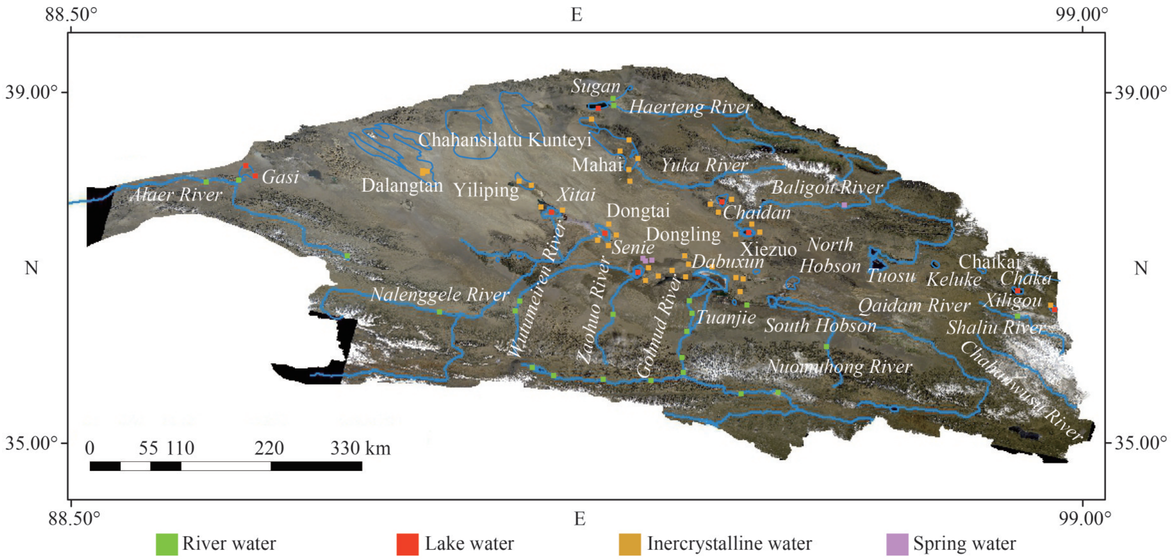

Fig.1 Remote sensing image of Qaidam Basin and water sampling points of different origins

blocking of moisture transport from the Indian and Atlantic Oceans (Thompson et al., 2005; Wang et al., 2008; Heermance et al., 2013), driving the Qaidam Basin toward extreme hyperaridity. These conditions promoted progressively enhanced evaporation, leading to the evolution of lake waters into saline brine systems (Zhang, 1987; Zheng et al., 1989).

Controlled by tectonic structures and physiographic conditions, Qaidam Basin developed a centripetal river network and formed two distinct hydrological recharge systems in its northern and southern regions. A total of 79 rivers are developed within the basin, predominantly seasonal, and mainly perennial channels such as Nalenggele River, Golmud River, Qaidam River, Halteng River, Bayin River, Nuomuhong River, Chahanwusu River, and Tataleng River. Nalenggele and Golmud rivers derive their discharges primarily from glacial meltwater and precipitation (Rao et al., 2021; Zhu, 2021; Tai et al., 2023), subsequently recharging Dongtai, Xitai lakes and Qarhan Salt Lake, individually. Qaidam River, located in the eastern part of the basin (Cheng, 2022; Cai, 2024), functions as a spring-fed tributary of the Xiangride River, flowing eastward into Huobuxun Lake. Nuomuhong River originates from east Kunlun Mountains and discharges northward into Huobuxun Lake as well (Yang et al., 2016; Xiao, 2017). In contrast, Bayin and Tataleng rivers, sourced from the Altun-Qilian Mountain system, are recharged by a combination of glacial melt and precipitation, ultimately feeding into Keluke Lake and Qaidam Lake (Zhang, 1987). As extensive water leaching and convergence, over 90 lakes of varying sizes, including 16 freshwater lakes, with the remainder being brackish or hypersaline develop in Qaidam Basin (Yang, 2019). Environmental changes have triggered notable area fluctuations in several of these lakes in recent decades (Wei et al., 2017; Cheng et al., 2024).

Drilling records reveal a well-developed stratigraphic succession in the Qaidam Basin (Zhu et al., 1994; Huang and Huang, 1996; Yuan et al., 2011; Li, 2019). The Mesozoic strata are predominantly composed of conglomerate, sandstone, mudstone, and sandy mudstone, primarily distributed along western Altun Mountains and the southern margin of Qilian Mountains. The Cenozoic strata, consisting mainly of mudstone, siltstone, and sandy mudstone, are widely exposed in the piedmont zones of Kunlun Mountains, western Qaidam, and northern Qaidam Basin. These formations currently serve as the primary hydrocarbon source rocks and oil reservoirs in the basin. The Quaternary deposits constitute the principal host layers for salt lakes. Notably, the western basin is characterized by calcium-rich minerals such as calcite and gypsum, while the southern basin is dominated by halite and potassium-bearing minerals (Fan et al., 2018).

3 SAMPLING AND TESTING

3.1 Sampling method

To investigate the distribution and enrichment mechanisms of K and Li in brine of Qaidam Basin, numerous published data and main water bodies in Qaidam Basin were systematically collected, including Dabuxun Lake, Senie Lake, Dongtai Lake, Xitai Lake, and some other rivers.

The sampling process strictly adhered to established protocols to ensure the sample integrity for analytical tests (Fig.2). Water samples were collected into pre-cleaned 500-mL bottles and each bottle was rinsed three times with in-situ water before sampling. Field measurements including pH, temperature, and density were immediately recorded using calibrated portable pH meter, thermometer, and densitometer. Geographic coordinates and elevation data were simultaneously obtained via GPS. To prevent leakage during transport and minimize evaporation under extreme conditions, all the bottles were sealed timely with adhesive tape at the cap interface. Each sample was duplicated (total 1 000 mL per site) and labeled with unique codes on both bottle body and cap using ethanol-resistant markers.

3.2 Sample testing

Concentrations of Cl^-, Na^+, K^+, SO_4^{2-}, Mg^{2+}, Ca^{2+}, CO_3^{2-}, HCO_3^-, Li^+ for all samples were determined at the Institute of Geophysical and Geochemical Exploration, CAGS. Na^+, K^+, Mg^{2+}, Ca^{2+} concentrations were detected by plasma spectrometer (PE8300). The analytical errors of Ca^{2+} and Mg^{2+} concentrations were less than 0.2%, and those of Na^+, K^+ were less than 0.5%. Li^+ concentration was detected by plasma mass spectrometer (PE300Q), the errors were less than 2%. Cl^- and SO_4^{2-} concentrations of water were detected by ion chromatography, and the errors were less than 0.2%. CO_3^{2-}, HCO_3^- were detected by HCl titration and follow the procedure of Methods for Analysis of Groundwater Quality (Geological and Mineral Resources Industry Standard of the People's Republic of China: DZ/T0064.49-2021)(Ministry of Natural Resources of the People's Republic of China, 2021). pH values were measured by Hana HI9126 portable pH acidity meter, the error was less than 1%. Brine densities were measured by DMA35 portable densitometer with a measuring accuracy of less than 0.1%.

4 RESULT

All testing data of brine and rivers are shown in

Fig.2 Sampling points in the Qaidam Basin

a. for intercrystalline brine; b. for lake water; c. for river water; d. for spring water.

Appendix 1. The total dissolved solids (TDS) of intercrystalline brines in most salt lakes generally exceed 200 g/L, with an average value of 330 g/L and a mean K content of 9.37 g/L, which was significantly higher than the industrial grade standard of 0.5% (Wang et al., 2020). Overall, intercrystalline brines from salt lakes in the western and northern Qaidam Basin exhibit lower TDS compared to those in the southeastern part of the basin, while their K contents are mostly below 5 g/L. A similar trend is observed for Li concentrations in the brines. In northern Qaidam Basin, such as Dalangtan and Mahai, Li contents in intercrystalline brines are predominantly below 25 mg/L. In contrast, the central basin regions, including Yiliping, Dongtai, Xitai lakes, and Bieletan mining area of Qarhan Salt Lake, show highest Li concentrations, all exceeding 200 mg/L. Eastward from the Bieletan, Li content in intercrystalline brines drops sharply to below 100 mg/L, demonstrating pronounced regional zonation (Fig.3).

The hydrochemical characteristics of salt lake waters in Qaidam Basin exhibit a distribution trend similar to that of intercrystalline brines. In the northern part of the basin, TDS of surface lake brines is comparable to that of intercrystalline brines, though their K contents are slightly lower, likely being influenced to some extent by atmospheric precipitation or surface water inputs. From the northeastern to the central Qaidam Basin, salinity of lake brines gradually increased from less than 200 g/L to over 300 g/L, reaching its maximum in Qarhan Salt Lake, demonstrating a distinct zonal distribution pattern. Correspondingly, the potassium coefficient ($\omega_K \times 1\,000/\Sigma_{salts}$), which denotes the ratio of 1 000 times the K weight to the total salinity weight, initially increased and then decreased, peaking at 33.65 near the Yiliping and Xitai lakes. Eastward from Dongtai Lake, the potassium coefficient progressively declined.

Due to complex tectonic faulting in Qaidam Basin (Fig.1), numerous salt springs are distributed alongside. Due to limited accessibility, we collected salt spring waters from Qaidam Lake in the northern and spring waters from Triple-lake Fault Zone in the south only. The hydrochemical characteristics of salt springs in the Death Valley have been significantly changed after mixing into Nalenggele River (Li et al., 2021b). Due to lacking of available sample, thus salt spring water from Death Valley was excluded from this investigation. Qaidam spring waters in the north showed low TDS (<10 g/L) and K content (≤0.01 g/L). In contrast, the salinities of salt spring brines from Triple-lake Fault Zone in the south were comparable to intercrystalline brines in Qarhan Salt Lake mining areas, with peak values exceeding 600 g/L, which far surpassed the mining-area brines in evolutionary stage. The average K content (4.27 g/L) was slightly lower than that of intercrystalline brines in the mining area, while the Triple-lake Fault Zone brines display higher TDS, some springs exhibit potassium coefficients ($\omega_K \times 1\,000/\Sigma_{salt}$) below 1—lower than those of northern marginal springs at average content of 4.7—likely reflecting potassium mineral precipitation. Lithium distribution shows marked variability: southern springs contain higher absolute Li concentrations, whereas Qaidam springs in the north demonstrate elevated lithium coefficients ($1\,000 \times Li/\Sigma_{salt}$).

Due to evaporation effects, TDS of rivers progressively increase downstream based on the test data, accompanied by rising K concentrations. Notably, only Wutumeiren and Tuolahai Rivers exhibit significantly elevated Li levels, with their lithium coefficients ($1\,000 \times \omega_{Li}/\Sigma_{salt}$) reaching 0.38. In contrast, all other surface rivers in the Qaidam Basin display lithium coefficients below 10%, demonstrating pronounced geospatial distribution characteristics.

5 DISCUSSION

5.1 Water type of brine

Based on the chemical differentiation theory proposed by Hardie (1984) and Eugster et al. (1980), the Spencer ternary diagram is commonly employed to investigate brine types and indicate their evolutionary pathways (Hardie, 1983; Lowenstein et al., 1989; Smoot and Lowenstein, 1991; Spencer, 2000; Ma et al., 2011). In the Ca-SO_4-ALK ternary diagram, lines connecting the SO_4 vertex with the calcite and gypsum precipitation points divide the diagram into three distinct fields: the Ca-Cl phase, Cl-SO_4 phase, and Na-HCO_3-SO_4 phase. With progressive evaporation, continuous crystallization of minerals such as calcite and gypsum in natural water drives hydrochemical evolution from Na-HCO_3-SO_4 phase through Cl-SO_4 phase, and under specific conditions, ultimately into the Ca-Cl phase. Compared to Valyashko classification system, Spencer diagram offers a more intuitive and simplified representation and minimizing the influence of magnesium on hydrochemical evolution.

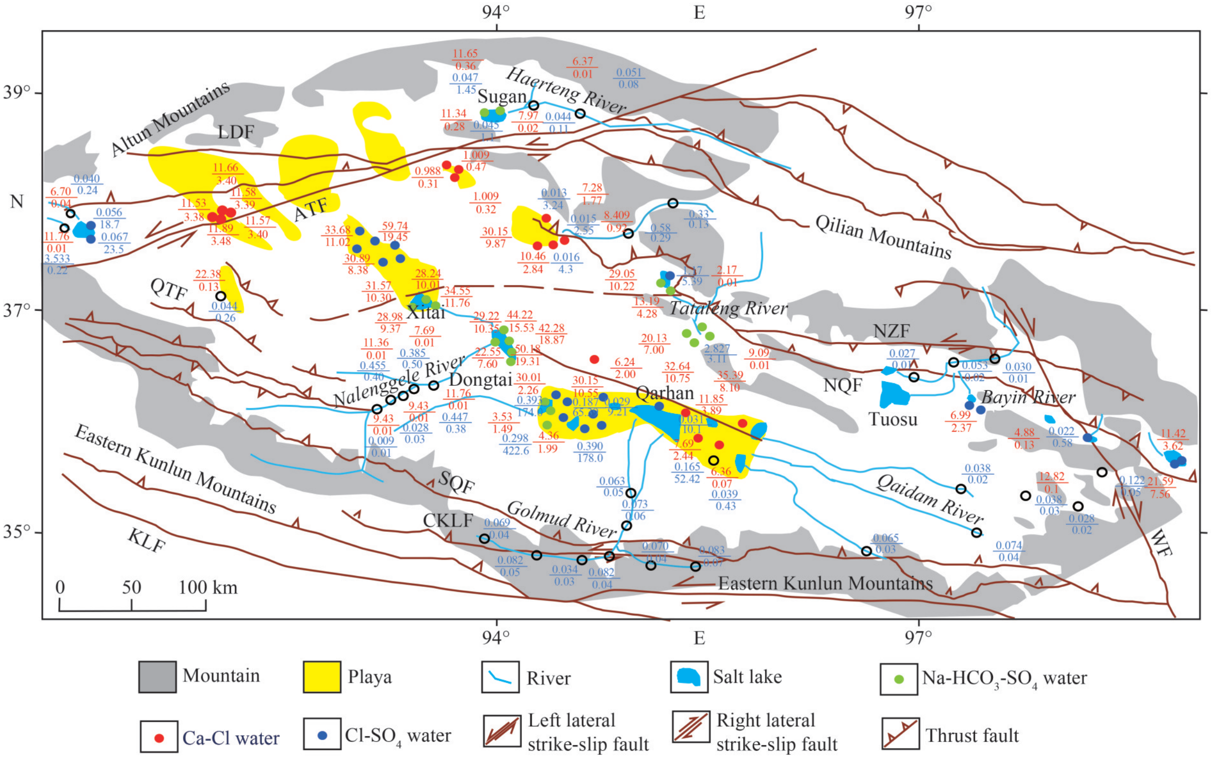

Fig.3 Geological map of Qaidam Basin and distribution of water types in Qaidam Basin with K and Li coefficient of water (Zheng et al., 2013; Zhang et al., 2022b)

In the *A*/*B* notation, *A* refers to the potassium/lithium coefficient of water. Red values indicate the potassium coefficient, and blue values indicate the lithium coefficient. The coefficient is computed as: *A*=1 000×*c* (K or Li)/TDS, where *c* is the value of K or Li (g/L), and TDS is the total salinity (g/L); *B* represents the absolute content of K or Li, with K expressed in g/L and Li in mg/L.

Hydrochemical plotting of the Qaidam Basin brines (Fig.4) reveals distinct evolutionary pathways for intercrystalline brines. Qaidan Salt Lake, Dongtai and Xitai lakes exhibit exceptionally high SO_4^{2-} concentrations (exceeding 60%) with Ca^{2+} concentrations below 5%, classifying brines within Na-HCO_3-SO_4 phase. In contrast, brines in northwestern basin, including those from Balun Mahai, lakes near Triple-lake Fault Zone, Niulangzhinü Lake, and Dalangtan Lake demonstrated Ca^{2+} enrichment (75%–90% cation equivalent) with low alkalinity and moderate SO_4^{2-}, diagnostic of Ca-Cl water type. Central basin salt lakes display intermediate characteristics, with Ca^{2+} concentrations ranging 0–40% and SO_4^{2-} predominance (>60%) alongside low alkalinity, resulting in Cl-SO_4 water type dominance (Fig.3).

Lake waters in Qaidam Basin are predominantly clustered in spatial distribution, with mostly classified as Cl-SO_4 type. Exceptions occur near Mahai and Yiliping, where brines show Ca-Cl type waters. Other lakes, like Senie Lake and Dongtai, Xitai lakes brines, defined as Na-HCO_3-Cl type water.

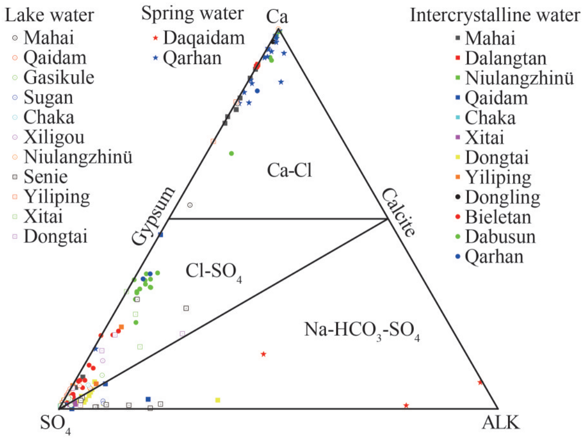

Fig.4 Ternary Ca-SO_4-ALK phase diagram of different types of water in Qaidam Basin

The salt spring waters near Triple-lake Fault of Qarhan Salt Lake exhibit a Ca-Cl hydrochemical type, characterized by Ca^{2+} contents exceeding 75%, coupled with ALK and SO_4^{2-} concentrations both below 15%. In contrast, salt springs near Qaidam display a Na-HCO_3-Cl water type, distinguished by

Ca^{2+} contents below 25%, SO_4^{2-} below 50%, and more than 50% ALK.

The hydrochemical composition of river waters in Qaidam Basin differs from that of brines (Fig.5), with most river waters exhibiting TDS below 20 g/L. In northeastern basin, rivers such as the Bayin and Huaitoutala display exceptionally low TDS, characterized by more than 30% Ca^{2+} dominance and Mg^{2+} contributions of 20%–35%, while other cations collectively account for less than 40%. Anion composition is dominated by CO_3^{2-}+HCO_3^-, constituting over 50% of total anions, with SO_4^{2-} as the secondary component. These rivers are classified as Na-Ca-CO_3 type waters.

In contrast, rivers in the north such as Mangya and Sugan river characterize as over 70% Na^+, minimal Ca^{2+} and Mg^{2+} content, and Cl^- as the predominant anion (>60%), corresponding to a Na-Cl water type.

The Yuqia River, originating from Qilian Mountains in the central basin, demonstrates Na^+ dominance among cations and CO_3^{2-} as the primary anion, as well as 40%–50% Cl^-, resulting in a Na-Ca-CO_3-Cl classification. Rivers emerging from northern Kunlun Mountains foothills exhibit moderate TDS (~1 g/L) with Na^+ constituting 60%–80% of cations and Cl^- representing ~50% of anions, categorized as Na-Cl type waters.

The Golmud River, sourced from Kunlun peaks, displays TDS generally <1 g/L. Its cation composition comprises 40%–60% Na^+, 30%–40% Mg^{2+}, and minor Ca^{2+}, while anions show consistent distribution: ~10% SO_4^{2-}, 25%–50% Cl^-, and 40%–80% CO_3^{2-}. Spatially, the upper Golmud River is dominated by CO_3^{2-} and Cl^-, minimal SO_4^{2-}, classified as Na-CO_3-Cl type. Downstream sections exhibit increased Cl^- (~50% anions) and reduced CO_3^{2-} (40%–50%), transitioning to a Na-Cl-CO_3 water type.

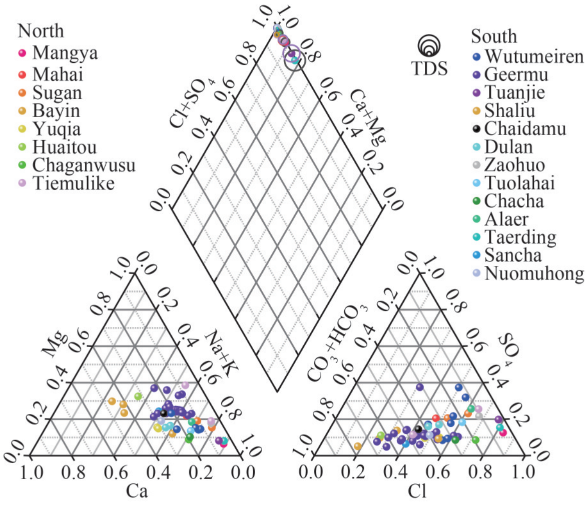

Fig.5 Water type of river water in the Qaidam Basin

5.2 Hydrochemistry characteristic

Brines in Qaidam Basin show different characteristics due to tectonic settings and brine migration (Feng et al., 2024; Han et al., 2025; Zhang et al., 2025). To find out the genesis and evolution process of brine in Qaidam Basin, geochemistry coefficients were applied (Niu et al., 2024; Shi et al., 2025).

The sodium-chloride coefficient (n_{Na}/n_{Cl}), which

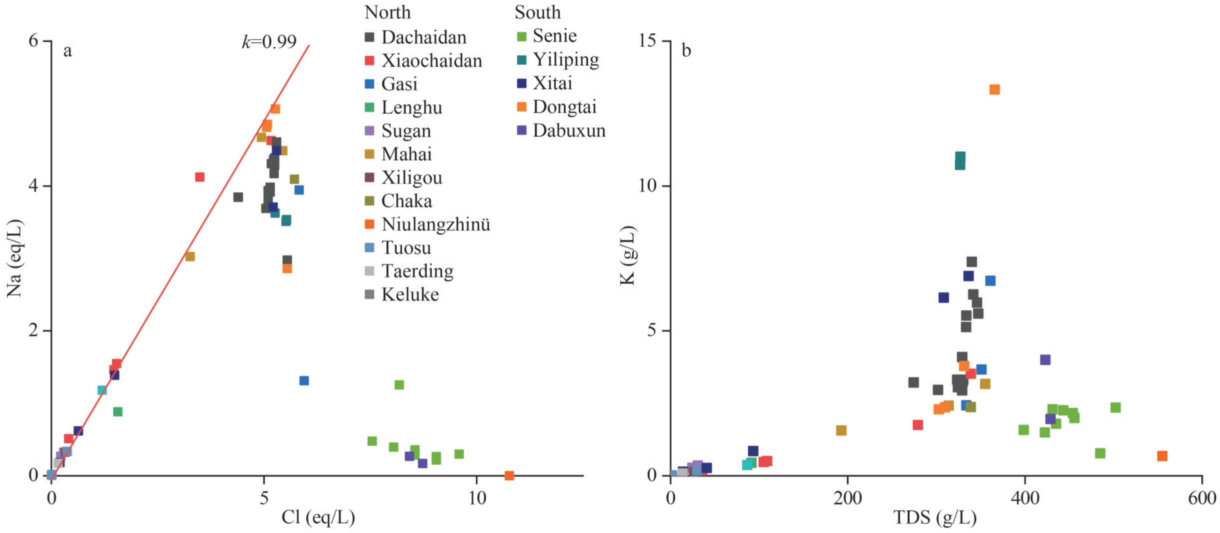

Fig.6 Relationship between elements of brines in Qaidam Basin

a. relationship between Na and Cl; b. relationship between K and TDS.

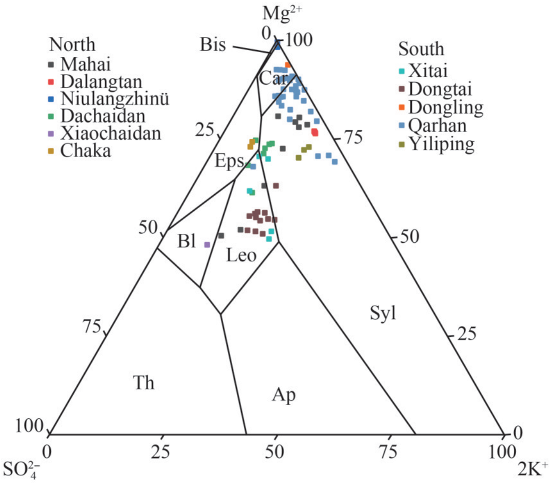

Fig.7 Distribution of brines in Qaidam Basin in the quinary system metastable phase diagram of Na^+, K^+, $Mg^{2+}//Cl^-$, SO_4^{2-}-H_2O at 25 °C

Bis: bischofite ($MgCl_2·6H_2O$); Car: carnallite ($MgCl_2·KCl·6H_2O$); Eps: epsomite ($MgSO_4·7H_2O$); Bl: bloedite ($Na_2SO_4·MgSO_4·4H_2O$); Leo: leonite ($K_2SO_4·MgSO_4·4H_2O$); Syl: sylvite (KCl); Th: thenardite (Na_2SO_4); Ap: aphthitalite ($K_3Na\ (SO_4)_2$).

denotes the molar ratio of Na to Cl, can be used to determine the primary sources of brine water bodies (Fan et al., 2007a, b). Research findings (Fig.6) indicate that intercrystalline brines of salt lakes in the Qaidam Basin all lie below a straight line with a slope of 0.99, though most deviate only slightly, exhibiting a clear leaching water origin (Feng et al., 2024). This suggests that glacial meltwater is the main recharge source for the salt lakes in Qaidam Basin. Intercrystalline brines of salt lakes in the northern Qaidam Basin have an average sodium-chloride ratio higher than those in the southern salt lakes, with most northern ratios exceeding 0.75, reaching their peak in Mahai-Qaidam Salt Lake. Due to large-scale recharge from piedmont water bodies, the northern salt lake brines are in crystallization stages of bloedite, leonite, and epsomite (Fig.7). In contrast, the southern salt lakes, such as Qarhan Salt Lake, Dongtai and Xitai lakes, and Yiliping Salt Lake, have intercrystalline brines with sodium-chloride ratios below 0.40. These waters have entered the sylvite-carnallite phase zone, demonstrating a far more advanced evolutionary stage than northern salt lakes and exhibiting characteristics of highly mineralized brine recharge. Notably, the intercrystalline brine of Niulangzhinü Lake in the north has a sodium-chloride ratio below 0.6, along with extremely high TDS, and its data fall within the carnallite phase zone, displaying distinct features compared to other northern salt lakes.

The potassium coefficient ($1\,000\times\omega_K/\Sigma_{salt}$) reflects the enrichment degree of potassium in brines and, to some extent, indicates the concentration level of the brine (Chen, 1983). In northern salt lakes of Qaidam Basin, potassium coefficient is mostly below 12, with TDS lower than 300 g/L, suggesting that the brines are still in the potassium concentration stage. However, Mahai Lake exhibits a potassium coefficient higher than that of the southern salt lakes, reaching around 30, indicating a notable potassium anomaly. Meanwhile, the southern salt lakes, such as Dongtai and Xitai lakes and Yiliping Salt Lake, mostly have potassium coefficients above 30, reflecting a more advanced stage of brine evolution.

The distribution of Li in Qaidam Basin exhibits distinct regional characteristics. Only a few salt lakes near alluvial fan of Nalinggele River and Qaidam Salt Lake have lithium concentrations exceeding 100 mg/L, while Li content in other lakes across the region remains relatively low.

5.3 Genetic analysis

Qaidam Block separated from the North China Plate during the Early Paleozoic due to the breakup of ancient continents, subsequently developing into a shallow marine environment (Qiu et al., 2021). With the northward subduction of the Indian Plate, Qinghai-Xizang Plateau experienced significant uplift, under the influence of a near N-S oriented stress field, Kunlun, Altun, and Qilian mountain ranges in the northeastern Qinghai-Xizang Plateau became tectonically active (Hu et al., 2016). This tectonic framework led to the formation of a high-mountain-deep-valley structural pattern in the northwestern Qaidam Basin (Zhang, 1987; Zheng et al., 1989), while Dalangtan and Shizigou regions evolved into long-term (~50 Ma) salt-forming centers (Zheng et al., 2016). Meanwhile, deep fluids arose along fault zones, which developed along Kunlun Mountain and Altun Mountain, supplying huge amount of K material and more than 80% Li material into surface water (Li, 2020; Miao et al., 2022). Influenced by persistent cold-arid environment since MIS 6 (Chen et al., 2017, 2020), precipitation and inflow water decreased but evaporation increased, water in Qaidam Basin gradually evolved from a Na-HCO_3-SO_4 water type to a Cl-SO_4 type. This hydrochemical evolution, coupled with pronounced chemical differentiation, resulted in extensive deposition of calcite and gypsum (Pan et al., 2022).

Under sustained subduction dynamics, Qaidam Basin has undergone five major tectonic events with significant basin reorganization (Zhu et al., 1990; Shen et al., 1993; Wei and Jiang, 1994). Gravitational settling drove the migration of depositional centers toward Dalangtan and Chahansilatu regions, where post-evaporative differentiation led to brine concentration in these areas, as well as Kunteyi depression, establishing critical K-Li enrichment zones. Concurrently, extensive mirabilite, halite, and potassium-magnesium salt deposits accumulated in the northern basin, reflecting the changes of temperatures from cold-arid to relative warm-arid condition.

During Late Pleistocene, reactivation of the central Qaidam fault triggered another major shift in depocenters (Zheng et al., 2015). Cl-SO_4 type brines, mixing with mountain-derived surface waters, migrated southward through Yiliping Salt Lake before final emplacement in Dongtai, Xitai and Qarhan Salt Lakes. Progressive evaporative evolution at these terminal basins generated world-class continental potash-magnesium-lithium deposits (Zheng et al., 2016; Liu et al., 2021; Li et al., 2022a, b; Li, 2022a; Rao et al., 2025).

The far-field effects of neotectonics activated the Kunteyi fault in Late Pleistocene, facilitating northward migration of residual brines along the structure (Fig.8). Due to the existence of the Altun Mountain front thrust structure, ancient salt was exposed and dissolved, supplying to Kunteyi. During the Holocene, mixed brines flowed from northern Kunteyi into Potassium Lake and Niulangzhinü Lake areas, precipitating extensive evaporites along the flow path and ultimately forming K-enriched salt lakes in the north of Qaidam Basin.

On the other hand, the recharge water significantly influences the distribution of K and Li elements in Qaidam Basin. Located in the hinterland of the Eurasian continent, Qaidam Basin is far from the Pacific Ocean, while the Himalayas and the Pamir Plateau block water vapor from the Indian and Atlantic Oceans. Consequently, glacial meltwater has become the primary source of recharge for the salt lakes in the Qaidam Basin. However, Ca-rich salt springs also recharge these salt lakes (Fig.9), particularly in Mahai, Kunteyi, Qaidam salt lakes, and lakes surround Triple-lake Fault area, acting as an additional source of K and Li for the formation of salt lake deposits (Chen et al., 1981; Li et al., 2021b; Li, 2022a).

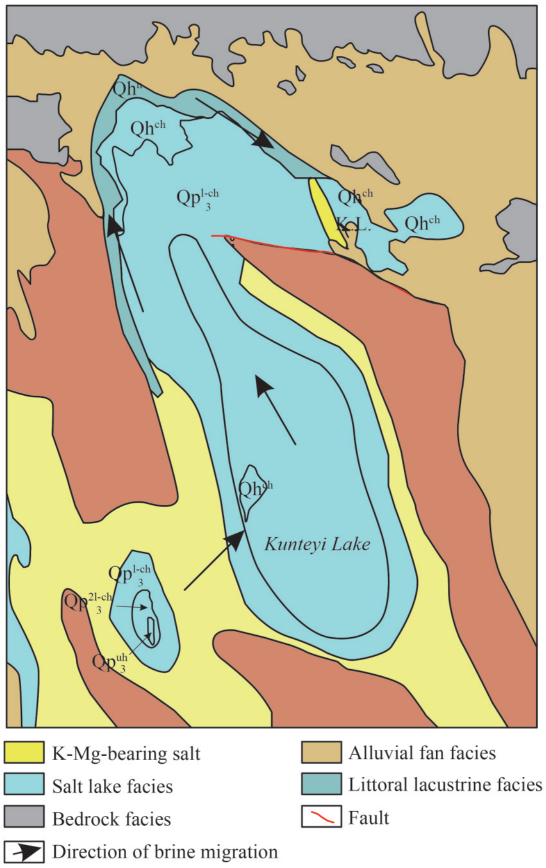

Fig.8 Direction of residual brine migration in Quaternary in Qaidam Basin

Taking Qarhan Salt Lake as an example (Fig.10a–b), intercrystalline brine in Qarhan mining section exhibited a high-K zone in its northern sector, with concentrations reaching up to 25 g/L, accompanied by TDS content of 370 g/L. In contrast, the southern part of mining area, due to strong hydraulic connectivity with Dabuxun Lake, showed lower TDS compared to northern region.

Dabuxun section, located in the central part of Qarhan Salt Lake, displayed a similar spatial distribution pattern of intercrystalline brine to Qarhan section. In Beiletan section, high-K zone was distributed in the northeast, with K concentrations reaching 19 g/L. However, influenced by the inflow of rivers such as the Golmud River and Qingshui River, both K and Li concentrations in the south were relatively low.

As the terminal lake of the Nalenggele-Wutumeiren River, Senie Lake brine, lies within the carnallite phase (Fig.7), resulting in low K content but an exceptionally high Li concentration, reaching

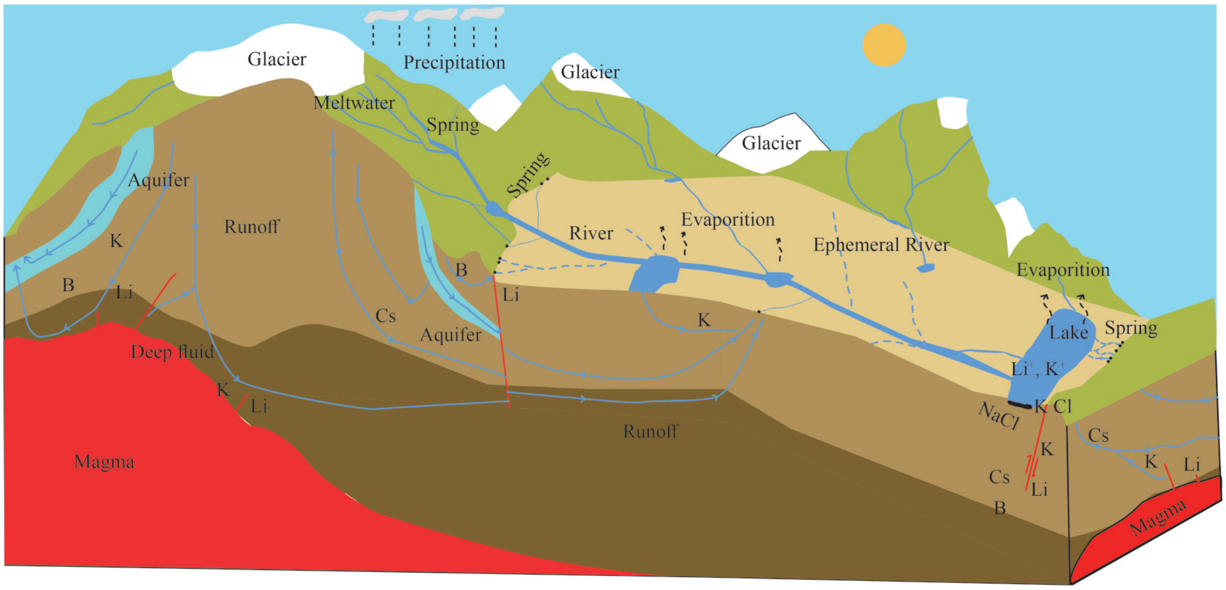

Fig.9 Schematic conceptual model of brine in the Qaidam Basin

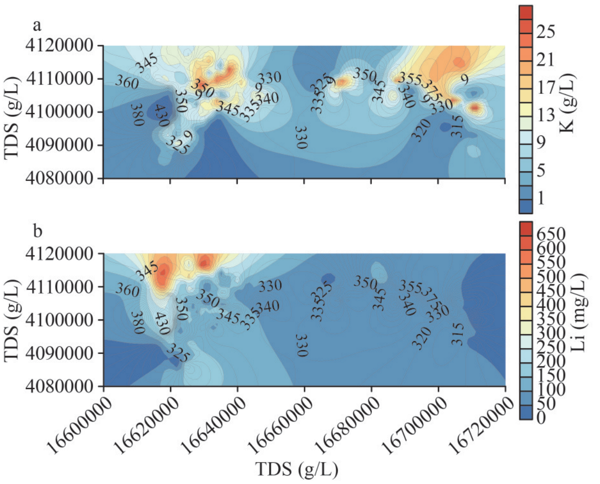

Fig.10 Distribution of K and Li with TDS contour line of intercrystalline brine in Qarhan Salt Lake

Figures as 350 indicate the contour lines of TDS (g/L) of the brine. Numbers such as 16660000 and 4080000 are Gauss-Krüger coordinates. a. distribution of K (g/L) in intercrystalline brine, Qarhan Salt Lake; b. distribution of Li (mg/L) in intercrystalline brine, Qarhan Salt Lake.

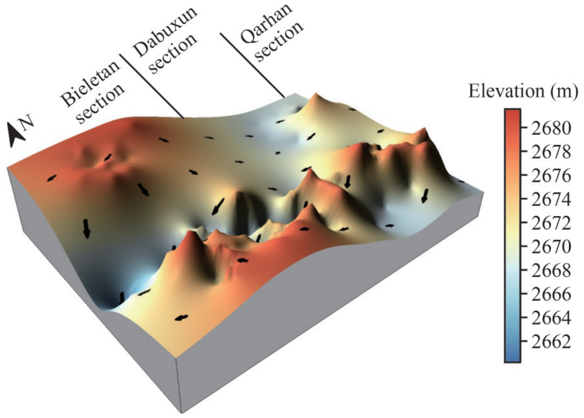

Fig.11 Simplified map of underground brine flow field in the Qarhan Salt Lake

up to 200 mg/L. Meanwhile, a high-Li anomaly zone was observed in the northern Beiletan mining area, with maximum Li concentrations reaching ~650 mg/L, which was significantly higher than those in Senie Lake.

Kriging interpolation method was applied to analyze water flow field of intercrystalline brine in Qarhan Salt Lake (Fig.11). The results reveal that the highest water occurs in the northern Beiletan area, with groundwater flow paths extending southward and eastward to Senie Lake and Dabuxun Lake, respectively. Due to the influence of Dabuxun Lake, water elevation in northern Qarhan Salt Lake was significantly higher than the south. Under gravitational forcing, salt springs originating from Triple-lake Fault zone migrated southward via subsurface flow, recharging the brine system. This influx of Ca-Cl-type brine has led to a systematic enrichment of dissolved elements, particularly K, and significantly altered the hydrochemical composition of brine. Consequently, the precipitation of sylvite (KCl) and carnallite ($KMgCl_3\cdot 6H_2O$) was accelerated, forming extensive evaporite deposits ahead of the normal evolutionary sequence.

Using the PHREEQC software developed by the USGS, hydrogeochemical modeling of the brine in Qarhan Salt Lake was conducted (Table 1). By mixing the average hydrochemical data of average

Table 1 Geochemistry of brine for PHREEQC test

Location	Water type	pH	Density (g/cm^3)	K (g/L)	Na (g/L)	Ca (g/L)	Mg (g/L)	Cl (g/L)	SO_4 (g/L)	CO_3^{2-} (g/L)	HCO_3^- (g/L)	Li (mg/L)
Qarhan	Spring	6.85	1.22	4.27	41.94	19.46	56.05	270.87	3.63	0.13	0.52	19.25
	River	7.00	1.00	0.01	0.10	0.05	0.04	0.17	0.12	0.03	0.24	0.11
Qaidam	Spring	8.50	1.00	0.01	0.33	0.02	0.00	0.35	0.19	0.00	204.35	3.11
	River	1.00	1.00	0.00	0.13	0.03	0.03	0.17	0.13	0.19	0.00	/

inflowing river water and salt spring water at different ratios, we found that different mixing ratios resulted in very different hydrochemical composition. When the mixing ratio of salt spring water to river water was set at 1:30, the hydrochemical characteristics of the brine closely resembled those of the salt spring water in the northern part of Qarhan Salt Lake, exhibiting a Ca-Cl water type. When at a mixing ratio of 1:60, the hydrochemical features of the brine were similar to those of brine in Qarhan mining area, characterized by a Cl-SO_4 water type. When the ratio was further increased to 1:100, the hydrochemical signature of the brine aligned with that of the middle and lower reaches of the Golmud River, displaying a Na-Cl-CO_3 water type.

6 CONCLUSION

Based on hydrochemical analysis of brines, salt springs, and river waters in Qaidam Basin, phase diagram analysis, and hydrogeochemical modeling, we concluded:

(1) Intercrystalline brines in Dalangtan, Balun Mahai, Niulangzhinü lakes and Qarhan Salt Lake exhibited high Ca but low SO_4 and ALK concentrations, behaving as Ca-Cl-type brines. Qaidam Salt Lake and Dongtai, Xitai lakes were characterized by elevated CO_3 and HCO_3, displaying a Na-HCO_3-SO_4 hydrochemical signature. Intercrystalline brines in Yiliping Salt Lake and western mining area of Qarhan Salt Lake showed Cl-SO_4-type characteristics. Lake brines in Mahai and Yiliping Salt Lake were classified as Ca-Cl-type waters. In contrast, Senie Lake, Dongtai and Xitai lakes, and Sugan Lake exhibited a Na-HCO_3-SO_4-type composition.

(2) Under the influence of tectonic gravitational forces, the sedimentary center had migrated from the northwest of Qaidam Basin toward the southeastern. This migration was accompanied by chemical differentiation, resulting in significant depletion of Ca and SO_4 in the northwestern basin while progressively enriching with Na, K, and Li. Then brines migrated from central basin underwent continuous evaporation and concentration, leading to further enrichment of K and Li. Similarly, driven by far-field effects of neotectonics, highly mineralized brines from Kunteyi Salt Lake migrated northwestward, transforming Niulangzhinü Lake and Potassium Lake into enrichment centers for K in the north. Salt springs serve as the primary source of Li in Qaidam Basin. Consequently, Li enrichment in brines predominantly occurs in Dongtai and Xitai lakes, as well as Beiletan mining section.

(3) Salt springs along faults in front of Altun Fault and Triple-lake Fault zones, contributed to salt lakes, which have increased the contents of Ca^{2+}, Cl^-, K^+, Li^+ in lake and intercrystalline brine with greater ratio of mixing with river water, accelerating the evaporation process in salt lakes, and further changing water types from Cl-SO_4 to Ca-Cl type.

7 DATA AVAILABILITY STATEMENT

Data will be made available on request from the corresponding author.

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Electronic supplementary material

Supplementary material (Appendix 1) is available in the online version of this article at https://doi.org/10.1007/s00343-025-5180-3.