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Geomorphic, hydroclimatic and hydrothermal controls on the formation of lithium brine deposits in the Qaidam Basin, northern Tibetan Plateau, China

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ABSTRACT

Qaidam Basin is a hyperarid inland basin with an area of 121×10^3 km^2 located on the northern Tibetan Plateau. Today, one fourth of the basin is covered by playas and hypersaline lakes. Nearly 80% of brine lithium found in China is contained in four salt lakes: Bieletan (BLT), DongTaijinaier (DT), XiTaijinaier (XT) and Yiliping (YLP). In the past decade, great attention was paid to improving the technology for the extraction of lithium from the brine deposits, but studies on origin and mode of formation of the brine deposits remained limited. Our recent investigations found that: (1) ~748.8 t of lithium was transported annually into the lower catchment of the four salt lakes via the Hongshui–Nalinggele River (H–N River), the largest river draining into the Qaidam Basin, (2) Li^+-rich brines are formed only in salt lakes associated with inflowing rivers with Li^+ concentrations greater than 0.4 mg/L, and (3) the water Li^+ concentration is positively correlated with both the inflowing river and the associated subsurface brine, including saline lakes with low lithium concentrations. These findings clearly indicate that long-term input of Li^+ from the H–N River controls the formation of lithium brine deposits. Here we determine that the source of the lithium is from hydrothermal fields where two active faults converge in the upper reach of the Hongshui River. The hydrothermal fields are associated with a magmatic heat source, as suggested by the high Li^+ and As^{3+} content water from geysers. Based on the assumption of a constant rate of lithium influx, we estimate that the total reserves of lithium were likely formed since the postglacial period. Our data indicate that lithium reserves in each of the four salt lakes depend on the influx of Li^+-bearing water from the H–N River. The data also suggest that during the progradation of the alluvial Fan I, the H–N River drained mostly into the BLT salt lake until the Taijinaier River shifted watercourse to the north and began to feed the salt lakes of the DT, XT and YLP, alongside with the Fan II progradation. The inference is consistent with stratigraphic evidence from the sediment cores of the four salt lakes. One of the major findings of our work is the importance of the contrasting hydroclimatic conditions between the high mountains containing ice caps and the terminal salt lakes. The greater than 4000 m of relief in the watershed enables a massive amount of ions, such as K^+, to be weathered and transported together with detrital material from the huge, relatively wet alpine regions to the hyperarid terminal basins, where intense evaporation rapidly enriches the lake water, resulting in evaporite deposition and associated K^+- and Li^+-rich brine deposits.

1. Introduction

The word "Qaidam", meaning salt marsh in Mongolian, characterizes the landscapes of the Qaidam Basin, where abundant brine deposits, such as KCl, are reserved in 25 salt lakes (Zhang, 1987). Lithium is also richly reserved in the brines of six salt lakes with a total of 15.2×10^6 t in LiCl (Zhang, 2000), which accounts for about 80% of the total brine lithium found in China. Most of the brine lithium is reserved in the four salt lakes of the Bieletan (BLT), DongTaijinaier (DT), XiTaijinaier (XT) and Yiliping (YLP) (Table 1). The BLT has the lithium reserves close to the average brine deposit (1.45 Mt Li) of the globe (Kesler et al., 2012). Similar types of the lithium brine deposits occur, for example, at the salar of Uyuni, Bolivia, although the climatic and geological settings are quite different. One of the major differences between the two settings is that the extensive outcrops of felsic volcanics occur around the salar of Uyuni (Tibaldi et al., 2009), whereas in the watershed of the four salt lakes only limited intermediate-felsic volcanic outcrops are found in the upper reaches of the Hongshui River (H-river) valley (Deng et al., 1996; Zhu et al., 2005). This difference is noteworthy regarding the origin of lithium because in Bolivia the alteration and weathering of the widespread volcanic rocks is likely the source of lithium for the formation of the lithium brine deposits (Risacher and Fritz,

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Table 1
Lithium reserves in the salt lake brines of the Yiliping (YLP), XiTaijinaier (XT), DongTaijinaier (DT) and Bieletan (BLT).Data from Cao and Wu (2004) and *Qinghai Salt Lake Industry Group Co. Ltd (2008).

Salt lake	Yiliping (YLP)	XiTaijinaier (XT)	DongTaijinaier (DT)	Bieletan* (BLT)	Sum total
Lithium reserves of brine deposit in $LiCl \times 10^3$ t	411	3084	2848	7740	14,083

2009). In the past decade, great attention has been paid to improving the technology for the extraction of lithium from the brine deposits of the four salt lakes because of the increasing market demand and lower production costs of recovering lithium carbonate from the brines. Studies on the origin and mode of formation of the brine deposits are scant. Two divergent hypotheses were drawn from pre-1990 investigations. One of the hypotheses proposes a multi-source contribution of lithium to the resource with emphasis on two possibilities: (1) a substantial contribution of lithium was from residual brines formed during the latest Pliocene in the saline lakes located in the western Qaidam Basin, which migrated eastward due to the basin's tectonic tilting and entered the Qarhan salt lake via the salt lakes of the YLP, XT, DT, and (2) the residual brines interacted with the Li-rich waters of other possible sources such as that from deep underground connate brines of Tertiary age, which facilitated the enrichment of lithium in the salt lakes since the late Pleistocene (Zhang, 1987). Another hypothesis emphasizes the important contributions of lithium from two ancient lakes, "Nalinggele Lake" and "Kunlun Lake", which possibly existed as large intermontane lakes in the Kunlun Mountains until 30 ka BP. The former was in the Nalinggele River valley and the latter was a huge intermontane lake south of the "Nalinggele Lake", receiving hot spring waters rich in Li, B, and K (Zhu et al., 1994). The tectonic-induced drainage into the Qaidam Basin of these two "ancient saline lakes", and several others within the eastern Kunlun Mountains is thought to be a primary cause of the commencement of evaporite deposition and ultimately the source of Li, B, and K in the Qarhan salt lake. Further investigation is required in order to (1) demonstrate why and how lithium-rich brines were formed solely in the Bieletan sub-playa but not in the other three sub-playas of the Qarhan salt lake, (2) improve our understanding of the main geomorphic and hydroclimatic controls on the formation and distribution of the lithium brine deposits, and (3) obtain firm evidence regarding the origin of lithium. With these objectives, a field observation and sampling campaign was carried out using data collection from previous investigations, detailed analysis of field data collected from related studies, and satellite images in the study area to identify set of nearly ideal sampling locations for the work described below.

The term hypersaline lake is defined here as a perennial surface brine either on a playa or as an individual water body with total dissolved solids (TDS) between 35 and 500 g/L. Playa, or salt flat, represents a flat-bottom depression with no surface brines for most of the year except during the flood season. It is associated with evaporites formed by receiving inland drainage from either perennial rivers, or ephemeral streams, with a negative water balance. Salt lake (Yan Hu in Chinese) has been used for many years as a term often representing not only a hypersaline lake, but also a salt flat or playa; the salt flat was named "Gan Yan Hu" in Chinese, meaning dry salt lake (Zhang, 1987). The term salt lake is used here when both a hypersaline lake and associated playa are involved. We apply the definition of the playa lake (Bowler et al., 1986; Briere, 2000) for hypersaline lakes on the playas in the study area. Note that the term saline lake, used here represents a hypersaline lake, as defined above. The terms described are applicable for salt lake studies in the Qaidam Basin, or for other arid and semiarid regions in China.

2. Geomorphic and hydro-climatic settings

2.1. Qaidam Basin

Qaidam Basin is the largest inland basin of the Tibetan Plateau with an average altitude of ~2800 m a.s.l. It is encircled by high mountains, the Altun to the northwest, the Qilian Mountain to the northeast, and the Eastern Kunlun Mountain to the south, which include Mounts Malan (6063 m a.s.l.), Buka Daban (6860 m a.s.l.) and Tahetuobanri (5972 m a.s.l.), all are topped by ice caps (Fig. 1). The Cenozoic evolution of the basin and its surrounding mountains is associated with the uplift of northern Tibetan Plateau within the framework of the India-Asia collision (e.g. Tapponnier et al., 2001; Yin et al., 2008). In the western half of the central basin folded sedimentary strata of Neogene to early Pleistocene ages cover more than a quarter of the basin. They have been sculpted by strong northwesterly winds, which are unimodal in direction (Goudie, 2007). The severe winds (up to 30 m/s in record) occur in relatively high frequency and cross over the lower elevation segments (3100–3600 m a.s.l.) of the Altun Mountain, forming the extensive fields of yardangs in the western half of the central Qaidam basin. Wind erosion was more severe during glacial and stadial periods when central Asia was colder and drier and the main axis of the polar jet stream shifted ~10° equatorward, placing it over the 3.88×10^4 km^2 mega-yardangs (Kapp et al., 2011). In addition to dry northwesterly winds, limited precipitation of 15–35 mm per year and high insolation collectively result in hyperarid environmental conditions with evaporation exceeding 2800 mm/year in the basin. Such basinal conditions also facilitate the formation of playas or hypersaline lakes, which occupy nearly a quarter of the Qaidam Basin. The development and distribution of playas or saline lakes depend largely on local hydrologic and geomorphic conditions. For example, windswept salt flats, namely, Kunteyi (KTY), Chahansilatu (CHS) and Dalangtan (DLT) in the western basin were formed within the yardang fields. These three playas are formed in the syncline depressions surrounded by rock hills of the Neogene sedimentary strata (Zhang, 1987). They receive surface runoff from alluvial fans developed along the piedmont of the Altun Mountain. Only ephemeral streams exist on the alluvial fans due to the intense aridity of the region. Despite the similarity in geological and climatic settings, drilling records reveal that neither the pattern of evaporite deposition nor the sedimentary stratigraphy above the Neogene rock strata appears to have synchronous characteristics, suggesting that deposition in each of the three playas is controlled by local geomorphic and hydrological processes (Huang and Han, 2007; Li et al., 2010; Zhang, 1987).

In the middle of the Qaidam Basin, salt lakes including playas and hypersaline lakes are all located in local terminal basins fed by rivers or streams, and their northern shores are bounded by the Pliocene–early Pleistocene rock strata. Among these salt lakes, the Qarhan Playa is the largest salt flat in the basin (Chen and Bowler, 1986; Yuan et al., 1995; Zhang, 1987), which exemplifies the distinct difference in terms of geomorphic and hydrological conditions when compared with aforementioned playas of the KTY, CHS, and DLT. Four of the five perennial hypersaline lakes lie around the edge of the Qarhan Playa and receive freshwater from rivers originating in the eastern Kunlun Mountains. They have hydraulic connections with subsurface interstitial brines in the halite-dominated saliferous strata interbedded with siliciclastic layers. Carnallite is the most common potassium mineral either disseminated in thin-layers on the lowermost locations of the playa surface, occasionally coexisting with bischofite, or as scattered crystals sometimes with aligned structure present in the salt strata of the playa deposits. With an area of 5850 km^2 the Qarhan Playa is the largest potash deposits found in China, having a total reserve of 194×10^6 t in KCl (Cao and Wu, 2004). K^+-rich brines are the dominant source used for the production of potash fertilizer, which are stored in the halite-dominated evaporite strata with porosities ranging from 20% to 30%.

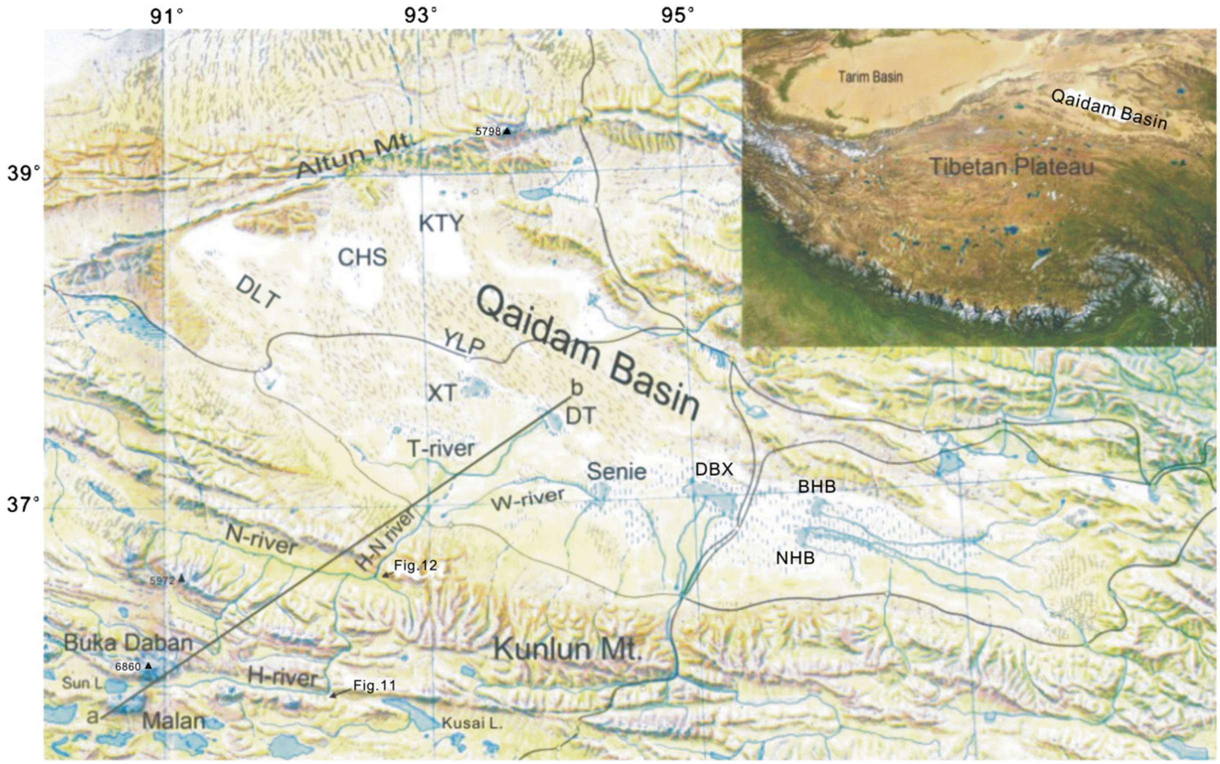

Fig. 1. Qaidam Basin, the largest inland drainage basin of the Tibetan Plateau, is encompassed by high mountains. The line a–b traces the topographic cross section on the map (see Fig. 3). About one quarter of the basin is covered by playas and saline lakes, in addition to large-scale coverage of the Yardangs. The inset map shows the location of the basin being on the northern Tibetan Plateau. Saline lakes on the map include the XT (XiTaijinaier), DT (DongTaijinaier), Senie, DBX (Dabuxun), BHB (BeiHuobuxun) and NHB (NanHuobuxun). Playas include the YLP (Yiliping), KTY (Kunteyi), and CHS (Chahansilatu). The Senie saline lake is located near the western margin of the BLT (Bieletan) playa (refer to Figs. 2 and 7 for the location of the BLT).

The Qarhan evaporitic sequence generally comprises three halite-dominated evaporite units separated by clastic-dominated sediment layers, among which only the topmost evaporite unit of 15 to 20 m thick shows a ubiquitous distribution over the entire Qarhan Playa. The lower two evaporite units are not present in the Huobuxun (HBX) sub-playa, which is the easternmost sub-playa of the Qarhan's four sub-playas (refer to Fig. 7 for location). The BLT sub-playa, located at the westernmost of the Qarhan, contains a complete sequence of the evaporite deposition of up to 70 m thick. Interestingly, Li^+-rich brines coexisting with K^+-rich brines occur only in the evaporite aquifers of the BLT, rather than of the entire Qarhan Playa. Also, studies of the nonmarine potash deposits of the Qarhan and associated brine evolution provide evidence that some anomalous marine evaporites may have formed from nonmarine brines rather than from seawater (Lowenstein et al., 1989).

2.2. Catchment of the BLT, DT, XT and YLP salt lakes

The saline lakes of DT, XT and Senie lie at sub-depressions of low-lying land along the middle of the central Qaidam Basin under hyperarid conditions with precipitation limited to 15–35 mm/y and the evaporation to precipitation ratio exceeding 100:1. They are basically perennial water bodies, usually less than 1 m deep, that experience frequent fluctuations in water level from less than 0.5 m to 2.5 m, depending on the amount of inflowing water mainly from the H–N River, the largest of all rivers draining into the Qaidam Basin. According to Yang and Zhang (1996), the annual runoff of the H–N River is 10.3×10^8 m^3 on average. The H–N River actually comprises two rivers: the H-river and the Nalinggele River (N-river), as shown in Fig. 1. The upper catchment of the Sun Lake (4886 m a.s.l.) is the headstream of the H-river, although short term cut-off may occur during dry seasons. The Sun Lake is fed by meltwater from the ice caps on both Mount Buka Daban (6860 m a.s.l.) and Mount Malan (6063 m a.s.l.), in addition to the runoff from precipitation. The H-river flows from west to east along the narrow, high-mountain valley, where the well-known Kunlun Fault strikes parallel to the range. It bends to the north crossing the eastern Kunlun Mountains at N35°53′24″ and E92°13′42″ at an altitude of 4205 m a.s.l. The H-river is joined by one perennial and several ephemeral streams before it merges with N-river. The N-river stems from Mount Tahetuobanri and the main river flows eastward for about 170 km and meets the H-river at the location of N36°35′24.7″ and E92°36′24.8″ at an altitude of 3282 m a.s.l. It is named the H–N River from the merging point downstream.

The H–N River has deposited a 1470 km^2 alluvial fan with a gradient of one in five hundred on piedmont of the northern Kunlun (Fig. 2, Fan I). Further progradation of the Fan I was blocked by a bedrock hill. As a consequence, the Taijinaier River (T-river) is constrained along the southern foot of the hill, collecting drainage from the alluvial fan. The T-river today is one of the major perennial rivers of the H–N River system in the basin. It turns to the north at the eastern end of the bedrock hill, where another large alluvial fan (Fan II) was deposited, having attained the southern shores of both saline lakes of the DT and XT. The Fan II is 1472 km^2 with a general slope of one in nine hundred.

There is up to a 4000 meter difference between the ice caps in the upper catchments and the saline lakes in the central Qaidam basin (Fig. 3). Although continuous meteorological records are lacking for this isolated region of the eastern Kunlun Mountains, available data indicate that annual precipitation increases with elevation at rates of ~10–16 mm per 100 m (Zhang and Liu, 1985). Thus the estimated precipitation is between 150 mm and 280 mm per year in the mountainous areas. About 70% of the total annual precipitation occurs in summer months from June through September in contrast to the arid winter months. Short periods of precipitation are predominant and more often than not it rains during the night. The entire watershed is within the middle-latitude westerlies with little influence from the Asian monsoons.

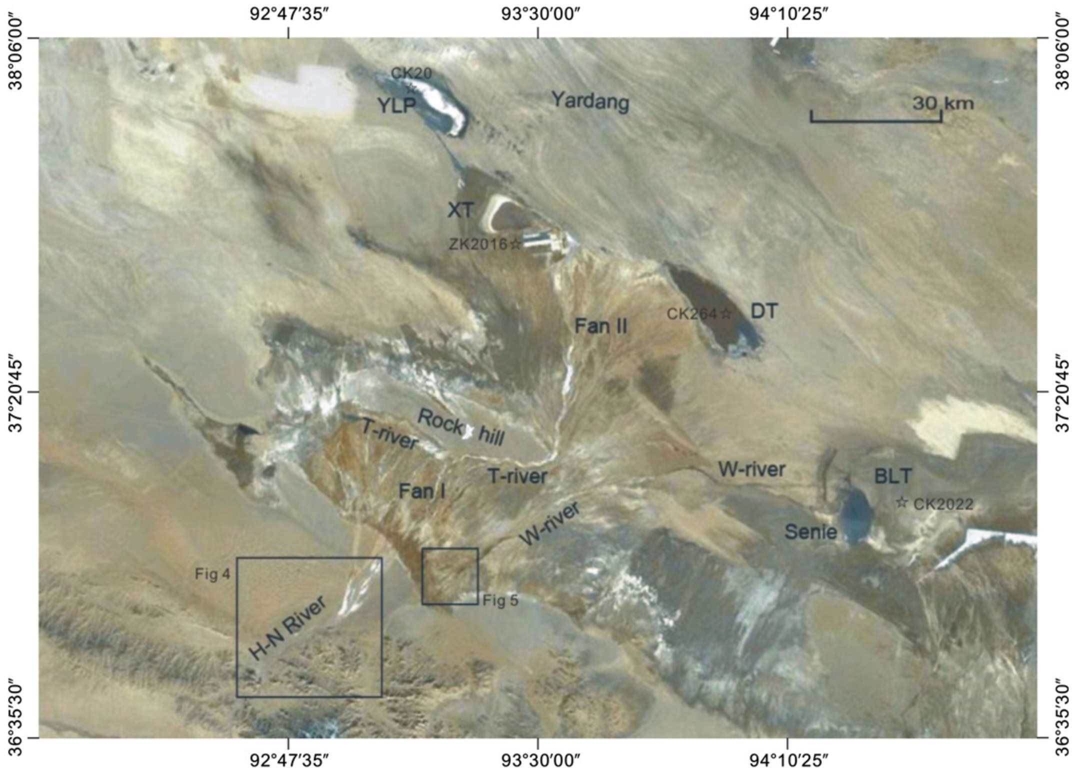

Fig. 2. Google image showing the salt lakes of Bieletan (BLT), DongTaijinaier (DT), XiTaijinaier (XT) and Yiliping (YLP), and two alluvial fans (named Fan I and Fan II) and associated rivers and streams draining into the four salt lakes. Stars mark the location of type cores from the four salt lakes.

To sum up, one of the prominent geomorphic features of the catchment is the strong contrast in height between the Qaidam Basin and the surrounding mountains, which results in differential effects on the dry westerly-dominated watershed with wetter conditions in high mountains and hyperarid conditions in the Qaidam Basin. Huge amounts of runoff from the large mountainous catchment transport a massive amount of dissolved ions and clastic material to the terminal basins. This leads to the formation of halite-dominated evaporitic deposits and associated K^+-rich interstitial brines. Lithium may also be enriched in the interstitial brines as long as the river-transported Li^+ is sufficient. This will be discussed and supported by the evidence presented in the following sections.

3. Evidence of prevailing contribution from river-sourced lithium

The lithium reserves in each of the four salt lakes of the YLP, DT, XT, and BLT are listed in Table 1. Accordingly, lithium concentration is distinctively higher in the surface and subsurface brines of the four salt lakes (Table 2), if compared with the brines of the HBX and Qarhan sub-playas (Table 3). In order to estimate the contribution of lithium from the H–N River to the four salt lakes, the river water was sampled from a 50-km reach of the H–N River (Fig. 4) and the measured lithium concentrations listed in Table 4. The averaging Li^+ concentration of the ten samples is used for calculating the total annual input of Li^+ ($\sum Li^+$, in tonne) into the lower catchment. The calculation is based on a simplified water and salt model:

$$\sum Li^+ = Q_{runoff} \times Li_{river} \times 10^{-6} \quad (1)$$

where the Q_{runoff} is the total annual runoff of the river in cubic meter and Li_{river} is the average Li^+ content of the river water in mg/L. By applying the values of $Q_{runoff} = 10.3 \times 10^8$ m^3 (Yang and Zhang, 1996) and $Li_{river} = 0.727$ mg/L (Table 4), the calculation yields an annual lithium input of 748.8 t from the H–N River into the Qaidam Basin. Providing that the H–N River is the only source of lithium contribution, it would take about 6000 years for the formation of the total lithium reserves (14×10^6 t in LiCl) in the four salt lakes. This is based on using the constant input rate of river-sourced lithium for

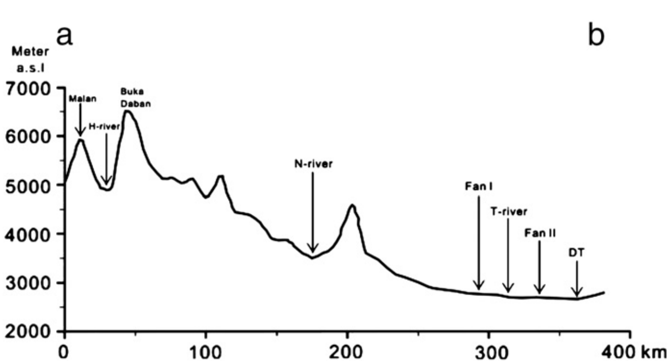

Fig. 3. Diagram of the cross section of the catchment (refer to Fig. 1 for location), displaying the prominent topographic differences of up to 4000 m in elevation between the ice caps of the eastern Kunlun Mountain and the terminal saline lake of DT in the Qaidam Basin.

Table 2
Selected chemical composition and properties (after Zhang, 1987) of the surface and subsurface brines of the salt lakes of the Yiliping (YLP), XiTaijinaier (XT), DongTaijinaier (DT) and Bieletan (BLT).

Name of salt lake	Type of water body	Date of sampling	pH	TDS (g/L)	Ions (mg/L)	
					K^+	Li^+
YLP	Subsurface brine	1980.6	7.3	327.2	11.0×10^3	262
XT	Surface brine of XT Lake	1980.6	7.7	336.3	6.9×10^3	202
	Subsurface brine	1980.6	7.9	344.6	8.4×10^3	256
DT	Surface brine of DT Lake	1980.6	7.7	331.5	3.8×10^3	141
	Subsurface brine	1980.6	7.9	344.6	8.4×10^3	256
BLT	Senie Lake	1980.6	7.1	333.0	7.3×10^3	191
	Subsurface brine of BLT playa	1980.6	6.5	358.0	23.2×10^3	124

Table 3
Chemical compositions and properties (selected according to the source of data as indicated in the table) of the inflowing rivers and associated saline lakes and subsurface brines in the four sub-playa areas of the Qarhan Playa. Refer to Fig. 7 for site locations.

Sub-playa	Type of water body	Date of sampling	pH	TDS (g/L)	Ions (mg/L)		Source of data
					K^+	Li^+	
BLT	Subsurface brine of the BLT	1980.6	6.5	358	23.2×10^3	124	①
	Senie Lake	1980.6	7.1	332.2	7.3×10^3	191	①
	W-river	1987	8.1	0.72	18.3	0.42	③
	DBL Lake	1980.6	7.0	362.9	8.5×10^3	37	①
	TL-river	1987	7.1	0.37	12.0	0.026	③
	XBL Lake	1980.6	6.2	386.9	18.9×10^3	66.3	②
DBX	Subsurface brine of the DBX	1980.6	6.7	331.8	19.0×10^3	26	①
	DBX Lake	1980.6	5.3	470.2	713	88.4	①
	XG-river	1987	7.9	0.34	4.15	0.03	③
	DG-river	1987	6.7	0.76	9.30	0.04	③
	DX Lake	–	7.4	262	3.4×10^3	–	②
Qarhan	Subsurface brine of the Qarhan	1980.6	7.0	321.5	12.1×10^3	15.6	①
	TJ Lake	1980.6	5.4	425.3	7.2×10^3	59.0	①
	XZ Lake	1980.6	5.5	358.5	7.7×10^3	28.6	①
	QJ-river	1987	7.5	0.36	14.9	0.12	③
HBX	Subsurface brine of the HBX	1980.6	6.7	311.2	3.0×10^3	10.3	①
	NHB Lake	–	7.9	313	3.6×10^3	13.8	②
	NM-river	1987	8.0	0.37	1.49	0	③
	BHB Lake	–	7.5	310	790	11.2	②
	QD-river	1987	8.2	0.38	3.0	0	③

① Zhang, 1987; ② No. 1 Team for Hydro-geological Survey, Qinghai Province; ③ Institute for Geological Studies of Mineral Deposits, Ministry of Chemical Industry.

the estimation and assuming a 50% loss introduced by factors such as en route adsorption. A more reliable calculation is yet unworkable because of lacking systematic record of the rivers runoff and related Li^+

Table 4
List for Li^+ concentration of water samples collected from the H–N River and W-river on Sept. 11, 2008. Refer to Figs. 4 and 5 for the locations of the sampling sites.

Sample number	Li^+ (mg/L)
H–N River water samples	
HN3	0.724
HN4	0.712
HN5	0.700
HN6	0.710
HN7	0.716
HN8	0.730
HN9	0.722
HN10	0.756
Water samples from streams into W-river	
Wm1	0.666
Wm2	0.654
Wm3	0.730
Wm4	0.800
Wm5	0.816
W-river water samples	
W1	1.406
W2	0.766
W3	0.758
W4	0.764
W5	0.764
W6	0.772
W7	0.768
W8	0.758
W9	0.772
W10	0.752
W11	0.818
Spring water samples	
Q1	0.628
Q2	0.630

Date of sampling: September 11, 2008.

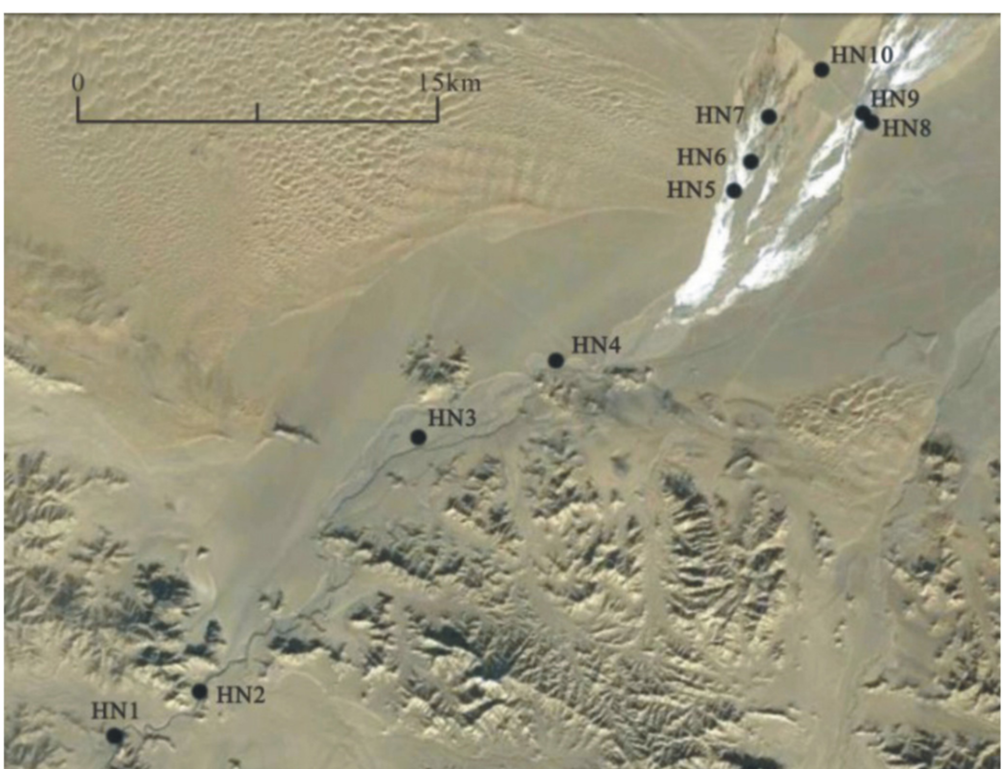

Fig. 4. Sites of water sampling along the H–N River. Refer to Fig. 2 for the location of the reach and to Table 4 for the Li^+ concentration of the water samples.

concentration data. Nevertheless, the estimation allows us to conclude that the total lithium supplied by H–N River runoff since the post-glacial period seems to be sufficient for the formation of the lithium-rich brine deposits in the four salt lakes.

Data from our investigation indicates that water Li^+ concentration of the W-river is as high as that of the H–N River (Table 4). This is not surprising because the W-river is intimately associated with the H–N River drainage. Field observations note many perennial and ephemeral streams draining from the Fan I eastward and feeding into the W-river, as shown in Fig. 5. Springs are common along the west bank of the W-river, seeping groundwater from the Fan I into the river. The prevailing portion of the annual runoff of the W-river relies on groundwater inflow from the alluvial Fan I, which provides a constant water supply for the river to maintain the Senie a perennial saline lake. Most importantly, continuous supply of the W-river water with high Li^+ content and evaporative concentration resulted in constantly high concentrations in Senie Lake with Li^+ concentrations fluctuating from 106 to 191 mg/L, nearly the same as that of the DT saline lake. The range of Li^+ content of the Senie Lake, on the other hand, remains about three times higher than that of the XBL, the ephemeral saline lake at the southeastern margin of the BLT sub-playa (Fig. 6 and Table 3). The XBL Lake is fed by ephemeral streams with low Li^+ content of 0.03 to 0.04 mg/L. The TDS of the XBL brine reached 386.9 g/L in June of 1980, whereas the Li^+ concentration remained as low as 66.3 mg/L. As shown in Fig. 6, a dilution effect may take place at site B12, where the Li^+ concentration in the 10-m-thick subsurface brine is as low as 56 mg/L, and it may still take place at site B11. The distribution pattern of Li^+ in the subsurface brines over the BLT sub-playa provides evidence that the W-river played a vital role in contributing Li^+ for the formation of the BLT lithium brine deposit.

The significance of river-sourced Li^+ for the formation of the lithium brine deposits is further confirmed by the evidence from investigation of three other sub-playas of the Qarhan. Based on available data as summarized in Table 3, we found that the Li^+ concentration of surface saline lakes is dependant on the Li^+ concentration of inflowing rivers. For example, the lowermost Li^+ concentration occurs in the brines of the BeiHuobuxun Lake (BHB) and NanHuobuxun (NHB) on the easternmost margin of the Qarhan Playa (Fig. 7),

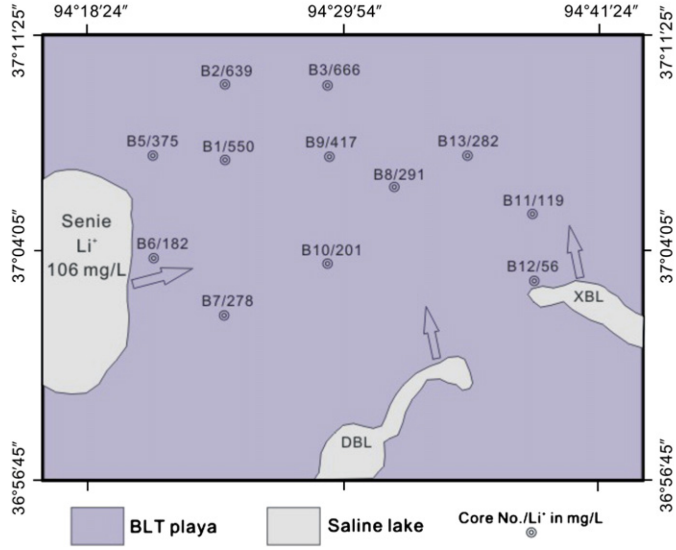

Fig. 6. Location of core sites on the BLT (Bieletan) playa (modified based on data from Tian et al., 2007). The indicated Li^+ concentration at each site represents the average content of Li in the top 10-m-thick subsurface brines. The arrows indicate general directions of horizontal permeable flow of the subsurface brines. The DBL (DaBiele) and XBL (XiaoBiele) are ephemeral saline lakes on the playa.

because the inflowing rivers (the QD-river and NM-river) contain very low concentrations of lithium. Similarly, in the sub-playa of the Qarhan and DBX, the Li^+ concentration of inflowing rivers is too low to allow lithium in the subsurface brine to reach the level needed for industrial utilization (generally above 100 mg/L), regardless TDS and K^+ concentrations are consistently high with values above 300 g/L and 7 g/L, respectively. In addition, the subsurface brine with high TDS values was centered in the east of the DBX, where relatively higher Li^+ concentrations in the brine reach 60 mg/L for the brine sourced from the west and 17 mg/L from the east (Wu et al., 1989). In short, all rivers and streams draining into the sub-playa areas of the DBX, Qarhan and HBX (Fig. 7) contain lower Li^+ concentrations by an order of magnitude if compared with the W-river.

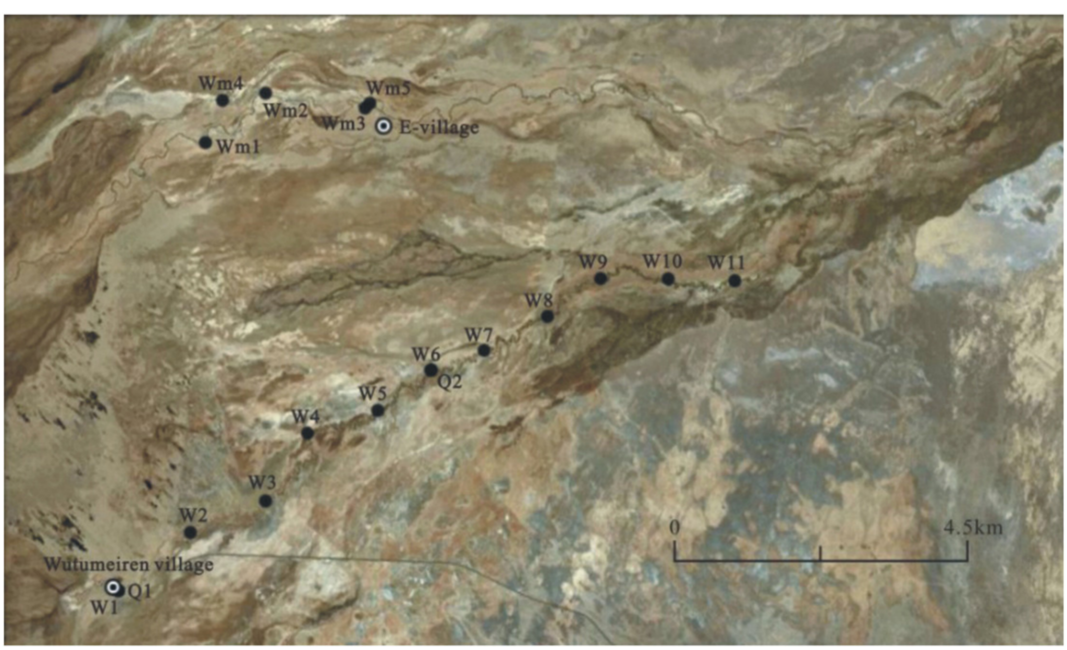

Fig. 5. Sites of water sampling along a part of the W-river. Refer to Fig. 2 for the location and to Table 4 for the Li^+ concentration of the water samples. The W-river is fed by a number of streams and springs as a result of surface and subsurface discharges of waters from Fan I.

Long-term input of such water limits the enrichment of Li^+ in the brines of the HBX, Qarhan and DBX sub-playas. Moreover, the data imply that brines located deep underground are an insignificant source of Li^+, because, if significant, the subsurface brines of the sub-playas would have much more enriched in Li^+ as a result of the upflow of connate brines with Li^+ content of more than 100 mg/L through faults either along the northern edge of the playa (Zhang, 1987) or across the three sub-playas (Yuan et al., 1995).

4. Origin of lithium for the brine deposits

The data and field observations presented here allow us to conclude that lithium in the brine deposits of the DT, XT and YLP originated from the continuous supply of river water with high concentrations of lithium. The majority of this lithium enriched river water came from the H–N River via the T-river and associated ephemeral streams on the Fan II. There is no doubt either that lithium in the brines of the BLT is also from the prevailing inflows of the H–N River system. Further, we were able to trace the source of lithium upstream to the mountain areas in the upper reaches of the watershed. The H-river is found to be the main lithium provider for the H–N River system, rather than the N-river. This is proven by the fact that the Li^+ content of the N-river water is only 0.04 mg/L (Zhu et al., 1990), as limited as that of other rivers draining into the sub-playas of the DBX, Qarhan and HBX, whereas the H-river waters contain much higher concentrations of Li^+, 8.50 mg/L in the upper reach water (Zhu et al., 1990) and 2.22 mg/L in the middle reach water (Li, 1996). The Li^+ concentration of the H-river decreases downstream as more branches join the main river. A prominent decrease occurred where the H-river merges with the N-river. The Li^+ concentration of the H–N River decreased below this point to 0.727 mg/L. Therefore, it seems evident that the merging of the N-river resulted in a dilution of the Li^+ concentration of the H-river.

We also found convincing evidence for the origin of lithium in the upper reaches of the H-river, based on a detailed analysis of the data collected from recent investigations on Cenozoic tectonics, volcanism and earthquakes in the study areas. As mentioned before, the main upper reach of the H-river flows along the narrow, high-mountain valley; the Buka Daban–H-river segment of the Kunlun Fault strikes along the northern side of the valley for approximately 100 km. In the last 100 years, five large earthquakes ($M \geq 7.0$) occurred along the Kunlun fault system (Fu et al., 2005), among them was the 2001-11-14 M_s 8.1 earthquake that produced a coseismic surface rupture of more than 400 km in length with a maximum displacement of 16.3 m of the left-lateral strike-slip fault (Lin et al., 2002). Such a coseismic surface rupture is the longest ever recorded for an intracontinental earthquake (Fu et al., 2005). Further westward from the western end of the Buka Daban–H-river segment, the active Kunlun Fault system becomes complex and comprises a series of faults striking a horsetail pattern (Klinger et al., 2005). Outcrops of volcanic rock are found in the upper H-river valley near the western end of the Buka Daban–H-river segment: (1) a 200 km^2 eroded lava platform on the northwest slope of the Mount Wuxuefeng (Deng, 1998) and a total thickness of ~180 m (Zhu et al., 2005), which is mainly composed of trachyandesite topped by pantellerite (Zhang and Zheng, 1996), (2) corraded table-like volcanics with reddish pumice and occasionally cinder as top layers, that covers on sandy slate at the Luangoushan in the northeast slope of Mount Malanshan (Zhang and Zheng, 1996), and (3) a small volcanic rock field characterized geomorphologically by lava dome and plug northeast of the Sun Lake (Zhu et al., 2005). Potassium–argon dating of the volcanics indicates that the most widespread volcanic eruptions occurred during the Miocene in the Hoh Xil area (Deng, 1998). Based on Ar–Ar dating results, Zhu et al. (2005) suggest that the late Miocene–early Pleistocene is another major period of volcanic activity, although the intensity and dimension of these eruptions are less than the earlier period of the Cenozoic. For comparison, the alteration and weathering of widespread volcanic rocks, especially ignimbrite strata surrounding the Andean salars, such as the salar of Uyuni, is considered to be the source of lithium production for the formation of the lithium-bearing brine deposits (Risacher and Fritz, 2009). It is however unlikely that the H-river could receive sufficient lithium in this way because of the patchy and limited distribution of the Cenozoic volcanics in the H-river valley. Instead, lithium-rich water discharged from hot springs is observed to be the dominant source of lithium entering into the H-river.

A hydrothermal field with hot springs is situated on the southern piedmont of the Mount Buka Daban (Fig. 8). There are about 150 geyser vents either steaming hot vapor with little H_2S or erupting hot water with temperatures up to 92 °C, which exceeds the boiling point altitude at 5000 m a.s.l. by about 7 °C (Klinger et al., 2005;

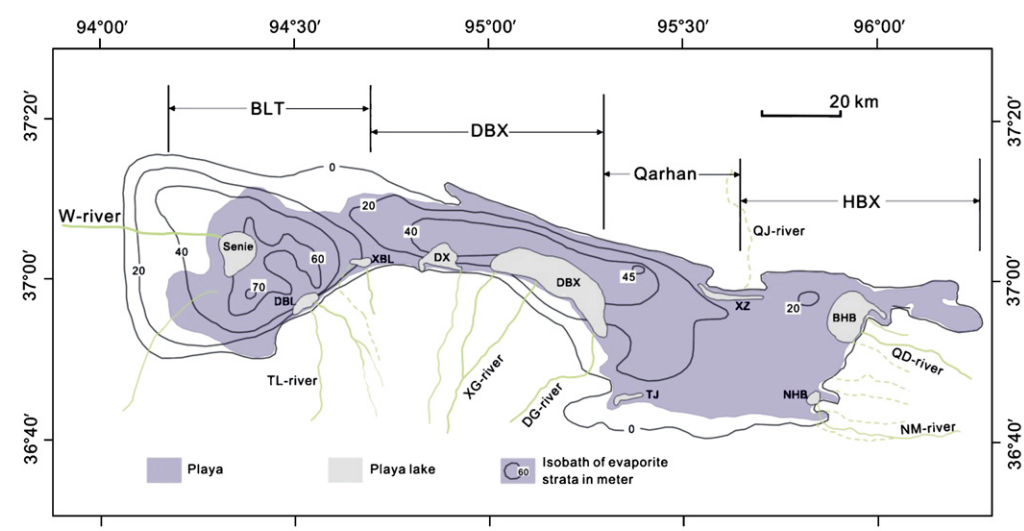

Fig. 7. Sketch map of the Qarhan Playa (blue) prior to the exploitation of the brine deposits. Hypersaline lakes (light blue) are formed around the margin of the salt flat, fed by inflowing rivers. The subsurface thickness and configuration of evaporite strata are illustrated by the isobaths, drawn based on data from Yuan et al. (1995). The Qarhan is divided into four sub-playa areas, namely, Bieletan (BLT), Dabuxun (DBX), Qarhan, and Huobuxun (HBX). The initials TL-river stand for Tuolahai River; XG-river for XiGolmud River; DG-river for DongGolmud River; NM-river for Nuomuhong River; QD-river for Qaidam River; QJ-river for Quanji River; Senie for Senie Lake; DBL for DaBiele Lake; XBL for XiaoBiele Lake; DBX for Dabuxun Lake; NHB for NanHuobuxun Lake; BHB for BeiHuobuxun Lake.

Zhang and Zheng, 1996). The hot springs have high concentrations of Li, B and As at 96 mg/L, 180 mg/L and 46 mg/L, respectively (Li, 1996). Such high concentrations of the trace elements indicate that the hydrothermal activities are associated with magmatic heat source (Arehart et al., 2003). Based on field investigation and aerial photo observation, the hydrothermal field is located on the northern side of an active fault, that strikes N70° along the northern shore of the Lexiewudan Lake to the southern shore of Sun Lake and terminates at the intersection with the Kunlun Fault (Zhang and Zheng, 1996). The active fault is named the L–S–K Fault, as shown in Fig. 8. Along the northern shore of the Lexiewudan Lake, there are nearly one hundred spring vents that provide large amounts of freshwater with a temperature around 30 °C for the lake. This causes in the northern near-shore area of the lake to be ice free in the winter months despite a severely cold winter climate in the Hoh Xil area. The lithium concentration of the Lexiewudan Lake water is 171 mg/L (Li, 1996), implying that the warm spring waters, which are the dominant source of water supply for the lake, are likely associated with the geothermal activities along the active L–S–K Fault. In addition, a volcano vent is found right at the active fault at Hudongliang between the Lexiewudan and the Sun Lake, and the post-Pliocene tectonic activity has broadened the rupture zone of the fault (Zhang and Zheng, 1996). Sun Lake, the 40 meter deep fresh water lake, contains Li^+ concentrations of 0.3 mg/L, which must come from the geyser vents of the hydrothermal field, since the meltwater as the prevailing water supply contains Li^+ concentration as low as 0.009 mg/L (Li, 1996). Two other sets of hydrothermal fields, including one active and another inactive, were reported at the locations close to the northeast end of the L–S–K Fault where it intersects the main segment of the Kunlun Fault. Evidently, the hot spring water has resulted in a high Li^+ concentration in the upper and middle reaches of the H-river.

Volcanic rocks in the study area have SiO_2 contents between 58% and 77% (Deng et al., 1996; Zhu et al., 2005), which are the intermediate-felsic volcanics. Dating of the volcanic rocks indicates that the last eruption occurred during the early Pleistocene (Zhu et al., 2005). Horizontal and vertical displacements observed along active faults are a common phenomenon produced by frequent earthquake activity. Earthquake-induced enhancement of the geyser eruptions in the hydrothermal field was reported following earthquakes on July 14–16, 1973 (Zhang and Zheng, 1996; Deng, 1998). This phenomenon was observed again in mapping the rupture of the 2001 M_s 8.1 earthquake (Klinger et al., 2005). The heat source of the geothermal activities and high heat-flow are likely associated with an underground magma chamber. In the northern Tibetan Plateau, isolated crustal magma chambers exist with a range of sizes, as suggested by data from geophysical investigations (Deng, 1998). We believe that the existence of a magma chamber is central to any explanation of a geothermal origin for the lithium in our study. We believe this because (1) Li, with higher solubility than most other cations, may have been concentrated in flowing and cooling magma bodies and/or its accompanying aqueous fluids, and (2) little lithium is dissolved by leaching rocks and minerals unless the water is very hot, generally greater than 300–350 °C (Garrett, 2004). In other words, one possibility causing the hot spring water to be so concentrated in Li, As, and B is its close association with magmatic solution (White, 1957). Another possibility is due to the reaction of natural hot waters with volcanic rocks as long as appropriate temperatures and sufficient reaction times are satisfied (Ellis and Mahon, 1964). Both of these mechanisms for deriving the lithium in thermal waters require a convecting magma heat source: the former involves addition of Li-rich solutions from the magma, and the latter requires only heat transfer to allow leaching of lithium from lithium-rich volcanic rocks. The available data is insufficient to date to firmly determinate whether the Li in these hot springs was derived from alteration of the volcanic rocks or from magmatic differentiation at depth. Further investigation may shed more light on the interesting issue.

In summary, the upper reaches of the H-river flows eastward through the narrow, high-mountain valley, in which the Buka Daban–H-river segment of the well-known Kunlun Fault strikes along the northern side of the valley. The maximum north–south compression following the India-Asia collision occurred probably during the Miocene and the consequent uplifting and crustal thickening strengthened volcanic eruptions of the potassium-rich magma (Deng, 1998). Cenozoic volcanic activity in the study area was largely constrained by subsequent tectonic movements of the Kunlun Fault system, including the L–S–K Fault. Large earthquakes and coseismic rupture zones depict frequent sinistral strike-slip displacement of the main segments of the Kunlun Fault since at least the last two glaciations with an average rate of 10–12.5 mm/year (Van Der Woerd et al., 2002). Hydrothermal fields with numerous hot spring vents occur at around the location where two active faults are converged. Li^+ and As^{3+} concentrations of the hot spring waters are unusually high, suggesting that the hydrothermal activities are associated with magmatic heat source. Neotectonic constraint of the Kunlun Fault system on the hydrothermal activities is evidenced by the rupture zone of the 2001 M_s 8.1 earthquake, which crossed the hydrothermal field with aligned hot spring vents over a length of ~1.5 km (Klinger et al., 2005). The active Kunlun Fault may enhance hydrothermal activities. The H-river is fed collectively by glacier meltwater from the ice caps, surface runoff from catchment precipitation and groundwater seepage, and subordinately by hot-spring water with high Li^+ concentration in the upper reaches of the river. Such geologic, hydrogeochemical and geomorphic conditions ensure a long-term supply of dissolved lithium for terminal salt lakes in the Qaidam Basin.

5. Enrichment process and formation of the lithium-rich brines

5.1. Enrichment processes of Li^+ in the salt lakes

The terminal saline lakes receive pulses of the H–N River discharge between April and May during the period when winter snow melt

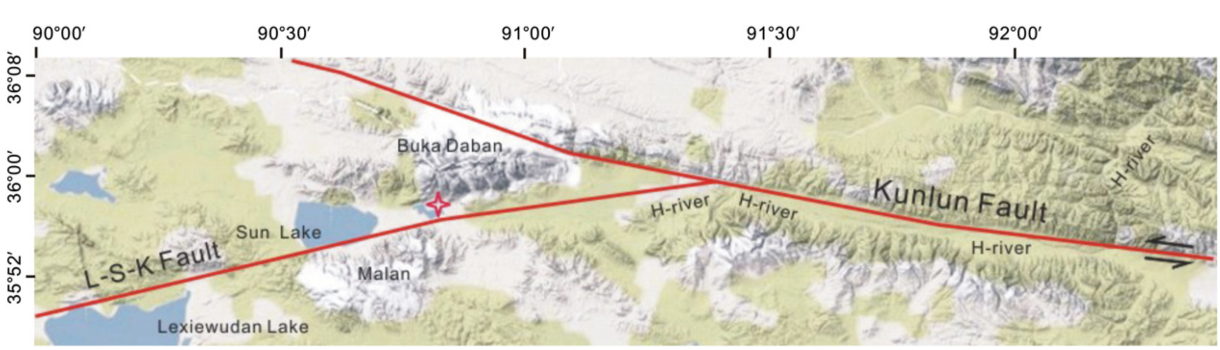

Fig. 8. Location of a geothermal field is shown by a red star. The 150-vent hot springs of the geothermal field lie at around the converging location of two active faults: the Kunlun Fault and the L–S–K Fault (Lexiewudan Lake–Sun Lake–Kunlun Fault).

and from July to August when seasonal flooding induced by concentrative summer precipitation in the mountain areas. The summer discharge is more pronounced and sometimes is disastrous. It usually amounts to 3 to 5 times more than the spring melt (Zhang et al., 2002). The enhanced discharge during the two seasons brings about a large amount of freshwater entering the terminal lakes, causing marked decrease in ion concentration of the surface brines (Fig. 9). The concentration of ions increases more or less in June as a result of enhanced evaporation following the spring flooding season, and then increases once again as soon as summer flooding takes effect. Subsequent increases in salinity and ion concentration attest to the effect of intense evaporation in the central basin. The seasonal changes in ion concentration, accompanying with rise and fall in lake area and level, are the annual process controlling the enrichment of ions in the brines, such as Li^+. More pronounced changes in lake area are recorded such as at the XT Lake, ranging from 116 km^2 (July 9, 1956) to near desiccation (July, 1988), and the largest lake area of approximately several hundred square kilometers in 1989 was reported due to a spate of river discharge as a result of abnormally high summer temperature and precipitation in the mountainous catchment. Changes in lake area can also be caused by the shifts of the T-river's watercourse on the Fan II, draining either into the DT Lake or the XT Lake. Noteworthily, the largest inflow in 1989 recorded since 1956 did not cover the entire area of the YLP salt flat by the overflows from the DT and XT, suggesting that the record large inflow was not of the largest since the post-glacial period.

The enrichment processes occurred in the Senie Lake and the BLT sub-playa are basically the same but with some important differences from what was described above for the salt lakes of the DT and XT. Evaporative concentration of Li^+ takes place in the surface brine as soon as the water of the W-river enters the Senie Lake, draining away a large portion of the inflow water by evaporation. Subsurface permeable flow horizontally with a speed of 0.11 to 0.12 m/day (Shaanxi, 2008) occurs synchronously toward the central and northern BLT sub-playa, together with the northward permeable flow of Li^+-poor water from the XBL and DBL (Fig. 6). As the phreatic water level of the subsurface brine ranges from 9 cm to 70 cm below the playa surface depending on the location and seasonal discharge, vertical evaporation takes place over the large salt flat. A long-term evaporative concentration of the surface and subsurface brines resulted in the distribution pattern of the Li^+-rich subsurface brines over the BLT sub-playa, as shown in Fig. 6. In regard to the response of the record large summer flood in 1989, the abnormal inflow has doubled the

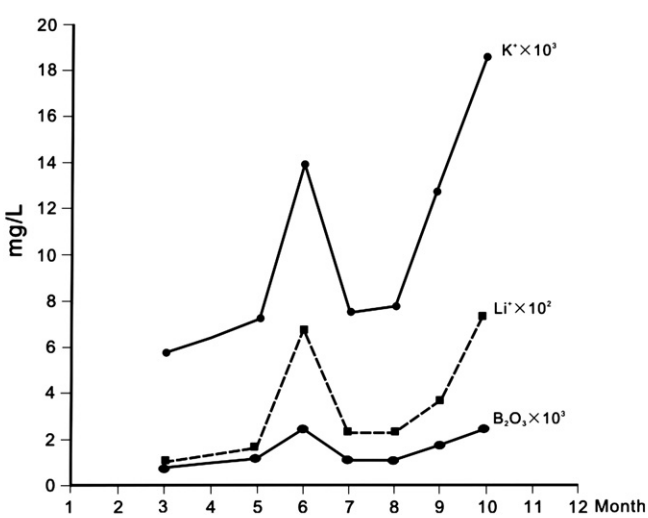

Fig. 9. Monthly measured concentrations of K^+, Li^+ and B_2O_3 in the surface brines of the XT in 2001 (after Zhang et al., 2002). Note that two lows in K^+ and Li^+ were resulted from the dilution effect of seasonal floods, which regularly occurred in two periods a year, namely, April–May and July–August, respectively.

size of the Senie Lake (Yuan et al., 1995). The Senie Lake was not as enlarged as the saline lakes of the DT and XT because it receives less drainage from the H–N River. Nevertheless, the largest inflow in record was unable to inundate the entire sub-playa of the BLT, even with help from the substantial expansion of playa lakes of the DBL and XBL. It is thus postulated that seasonal water influx from the W-river during the evaporite deposition of the subsurface layer at the 40 m isobath of the BLT (Fig. 7) exceeded that of today because the past deposition requires a larger inundated area over the playa. This inference is in full agreement with the concluding note from previous studies that the conditions necessary to deposit the halite over the Qarhan salt flat required greater input of water than is available today (Bowler et al., 1986).

Interestingly, the abnormally high summer precipitation in 1989 also resulted in a 0.5 m lake-level increase of the large Lake Qinghai, suggesting that a comparison of the paleoenvironmental records from Lake Qinghai and the four salt lakes is meaningful. The early–middle Holocene climate, for example, is characterized by higher summer temperature than today, as indicated by the proxy record of Lake Qinghai (Yu and Kelts, 2002; Yu and Zhang, 2008). In the mountainous catchment area of the four salt lakes, higher summer temperature could amplify the contrasting hydroclimatic conditions between the high mountains and the salt lake areas. In other words, more precipitation occurred in the mountainous catchment than today because vertical airflows, which trigger condensation in mountainous topography, were increased when the alpine surface was warmer. Meanwhile, aridity in the central Qaidam Basin was intensified with evaporation more enhanced than today. We thus propose that the early–middle Holocene was a favorable period for the deposition of evaporites at the salt lakes of the Qaidam Basin. The YLP playa, for example, probably received more overflows via the XT during the early–middle Holocene when the annual runoff of the H–N River was more than that of today. Similarly, the BLT sub-playa had a larger inundation area during the early–middle Holocene because of enhanced summer discharge, which was then followed by more intense evaporation than that of today.

5.2. Commencement of evaporite deposition and associated influx of water with high Li^+ concentration

The configuration of the BLT basin prior to evaporite deposition is defined by the isobath map in Fig. 7. The sketch map also illustrates the deposition pattern of the halite-dominated evaporites after the commencement of the evaporite deposition. As mentioned in the previous section, the tectonic-induced drainage of two mega paleo-lakes of "Nalinggele" and "Kunlun" into the Qaidam Basin is thought to be the primary cause for the commencement of evaporite deposition and the source of Li in the Qarhan salt lake (Zhu et al., 1990). In order to test this hypothesis, we examined the topographic and geological features of the mountain area. We noticed that the ancient "Nalinggele Lake" (though much smaller in size) was possibly present in the N-river valley before incision took place to allow the paleo-lake water draining into the Qaidam Basin via the H–N River (Fig. 1). However, the rock strata (Fig. 10) and the topographic feature (Fig. 8) provide little evidence for the pre-30 ka existence of the "Kunlun Lake". Firstly, the rock strata in the proposed paleo-lake area comprise mainly Tertiary molasse deposits along with reddish gypsum and carbonate rocks (Fig. 10). Secondly, the uplifting of the paleo-lake area is limited in the past 30 ka. Thirdly, the incision of the paleo-lake induced by north-to-south upstream erosion of the H-river, as proposed by Zhu et al. (1989), is unlikely because it requires a 700 meter deep water of the "Nalinggele Lake" to reach the elevation of 4200 m a.s.l. (Fig. 11, see Fig. 1 for location; and Fig. 3). Such a deep "Nalinggele Lake" is yet topographically impossible because the downstream drainage of the H–N River could easily take place, as long as the paleo-lake level reaches 3300–3400 m a.s.l. (Fig. 12, see Fig. 1 for location). Alternatively, we suggest that the incision at the site where the H-river bends sharply to the north (Fig. 11) is done by downstream erosion based on the following observation. The H-river could have overflowed eastward into the Kusai Lake (Fig. 1) if the H-river surface increased to above 4400 m a.s.l., assuming that the northward watercourse of the H-river was not yet incised. In other words, inasmuch as the west-to-east downstream flow of the H-river has a steep gradient of 5–7 m per one kilometer, it is fairly easy to incise a northward-flow watercourse at the river-bend site of 4200 m a.s.l. (Fig. 11) during flood seasons, under the condition that the south-to-north part of the H-river valley was shaped by previous tectonic movement of the region. Similar process of the incision could occur at the sharp bend site of the H–N River shown in Fig. 12, when the paleo-lake level in the N-river valley reached 3300–3400 m a.s.l. The topographic feature here does not seem to indicate favorable conditions for the existence of a mega, long-lasting paleo-lake in the valley of the N-river, because (1) the gradient of the 170-km west-to-east flow of the N-river is steep, about 5 m per kilometer, and (2) the area covered by the 3400-m contour represents a relatively smaller paleo-lake size, that is, its western shoreline was approximately at the Buluntai (Fig. 10).

Obviously, no evidence is found for the existence of two mega paleo-lakes. The following is an analysis on the basal configuration of the Qarhan basin prior to the evaporite deposition and the distribution pattern of evaporite strata over the Qarhan Playa. It suggests that the commencement of the evaporite deposition does not necessarily require large influx of saline water either from the mega paleo-lakes in the Kunlun Mountains (Zhu et al., 1990) or from the paleo-lake of the western Qaidam Basin (Zhang, 1987). As shown in Fig. 7, prior to the evaporite deposition, the Qarhan basin rose and fell in gentle folds and the BLT sub-playa area was a deeper and isolated sub-basin separated by a rise between the BLT and the DBX from other parts of the Qarhan basin. Evaporite deposition started first at the lowermost part of the BLT depression and the dimension of the paleo-saline lake was very small at the earliest stage. It had a surface area that was about one twentieth of that of Senie Lake, as defined by the 70-m contour. As the evaporite deposition expanded to the size of the 60-m contour in the fairly flat sub-playa area of the BLT, the DBX and Qarhan areas were most likely still in the pre-playa stage. Thereafter, a large salt lake was formed in the DBX and Qarhan sub-playas, with a size approximately shown by the 40-m contour of the evaporite strata (Fig. 7). However, evaporite deposition at that time did not initiate on the HBX area. The data suggest that the uniform Qarhan Playa was not formed until the uppermost evaporite strata of ~15 to 20 meter thick began to form. In other words, evaporite deposition at each individual sub-basin was largely determined by its own pre-playa configuration and the nature of inflowing river(s). The distribution pattern of Li^+ in inflowing rivers, surface and subsurface brines provides additional evidence of supporting the above-described depositional process and the pattern of the evaporite formation at the Qarhan Playa.

We believe that the water with high Li^+ content from the upper reaches of the H-river was initiated as early as the beginning of the evaporite deposition. The evidence found from the isobath map of the evaporite strata (Fig. 7) makes it clear, regarding the question why lithium brine deposit was formed solely in the BLT sub-playa rather than in the entire Qarhan salt lake, that the underground rising between the BLT and DBX sub-playas blocked the passage of H–N River water into the DBX.

5.3. Geomorphic constraint of shifting river drainage on the depositional system

It is evident that availability of the water from the H–N River system is an important factor in controlling the surface process of lithium enrichment in the four salt lakes. Overall, the more river water influx to the terminal saline lakes in the past, the greater the quantity of lithium reserved in the lake brines. The distribution ratio of total runoff of the H–N River is estimated roughly at 1:3.2 for the case of the BLT versus DT, XT and YLP, based on observational data from prior industrial utilization of the brines (Yuan et al., 1995; Zhang et al., 2002). Providing that the distribution ratio in the past was approximately the same as today, the total lithium reserves in the brines of the DT, XT and YLP should exceed that of the BLT. However, we know this is not true. In fact the lithium reserves in the BLT exceed the sum total of the DT, XT and YLP (Table 1), which requires an explanation.

By the geomorphic examination of the two alluvial fans, past alterations in stream flow pattern in association with the northward progradation of the alluvial fans were most likely responsible for the actual distribution of the lithium reserves in the four salt lakes. The present-day active parts of the Fan I are basically on the left side of the alluvial fan (Fig. 2) and most of the stream flows are collected by the T-river, draining into the DT and XT via the streams on the Fan II. From the beginning of and during the progradation of Fan I,

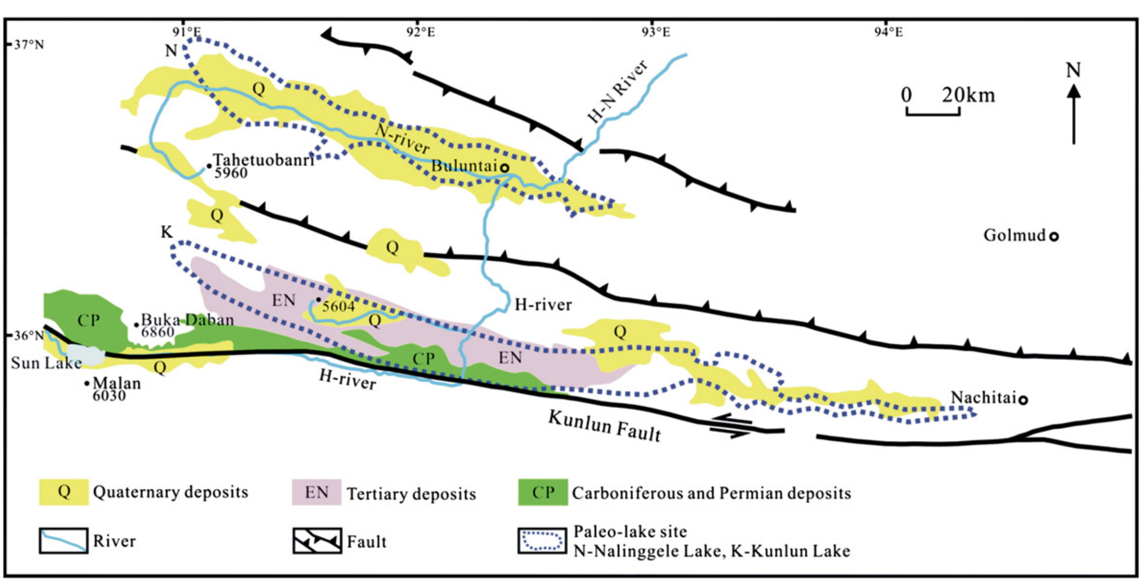

Fig. 10. A sketch geological map of the mountainous area of the watershed drawn based on data from the Geological Map of the Qinghai Province of 1:10^6-scale. It illustrates the ages and types of the deposits in the related areas where before 30 ka BP there might exist two mega paleo-lakes proposed by Zhu et al. (1990).

Fig. 11. The Hongshui River (H-river) bends from west to north at the site with an elevation of 4200 m a.s.l. Note that the altitude of the Sun Lake near the western end of the H-river is 4880 m a.s.l.

however, most of the streams, if not all, on the Fan I were draining into the BLT because of the following constraints. The elevation the DT Lake is about 6 m higher than the Senie today, but prior to the evaporite deposition, it was about 20 m higher, as revealed by stratigraphic records from a number of drill cores (Fig. 13). The paleo-topographic feature and the presence of the bedrock hill, in particular, must have resulted in the condition leading the river flows toward the Senie and the BLT. Following a long-term northward progradation of the Fan I, it approached the bedrock hill and the T-river began to form along the southern foot of the hill. It is reasonable to assume that the evaporite deposition of the DT, XT and YLP could not commence until the T-river shifted its west-to-east flow northwards, draining the prevailing surface runoff from the H–N River into the three salt lakes alongside with the Fan II progradation. This inference provides one of the best explanations of why the total lithium reserves in the brine deposit of the BLT exceeds the sum total of the reserves in the DT, XT and YLP, and on why the evaporite strata at the DT, XT and YLP are on average 20 m less in thickness than those at the BLT (Fig. 13). The inference is also consistent with the radiocarbon-age supported lithostratigraphic correlation that the evaporite deposition at the central BLT began from ~24.1 ka BP (uncalibrated ^{14}C age, Chen and Bowler, 1985), whereas at the DT, XT and YLP it started from about 13.7 ka BP (Zhu et al., 1994), some 8–10 ka later than that at the BLT.

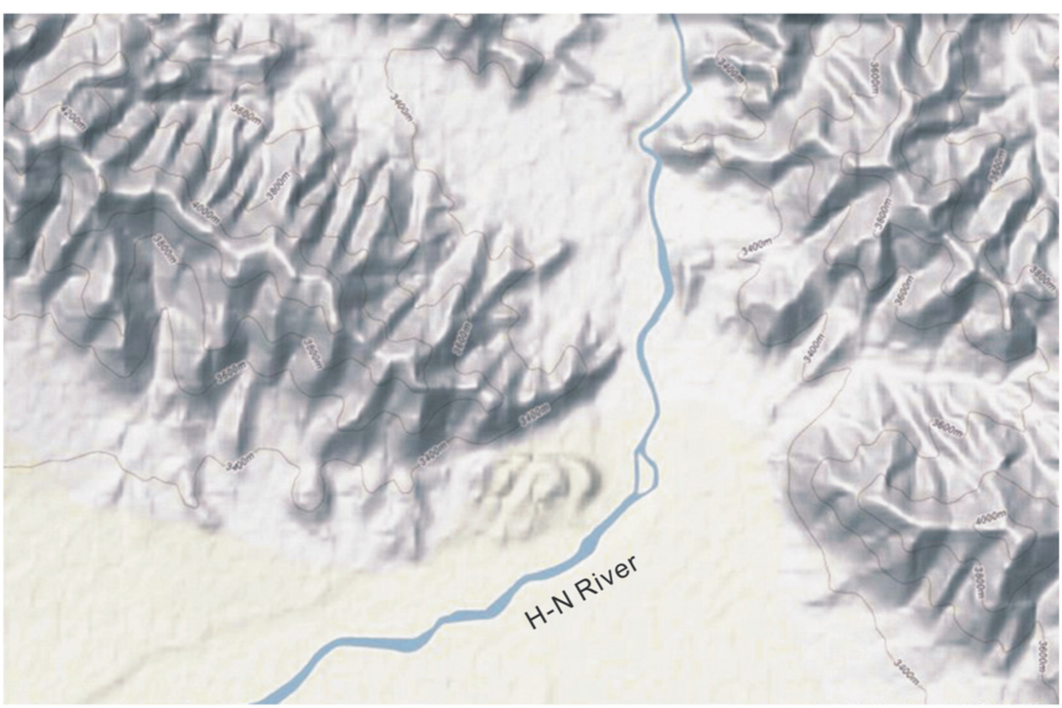

Fig. 12. The H–N River bends from west to north at the site with an elevation of 3280 m a.s.l. Note that the elevation at the starting point of the west-to-east flow of the N-river is 4100 m a.s.l.

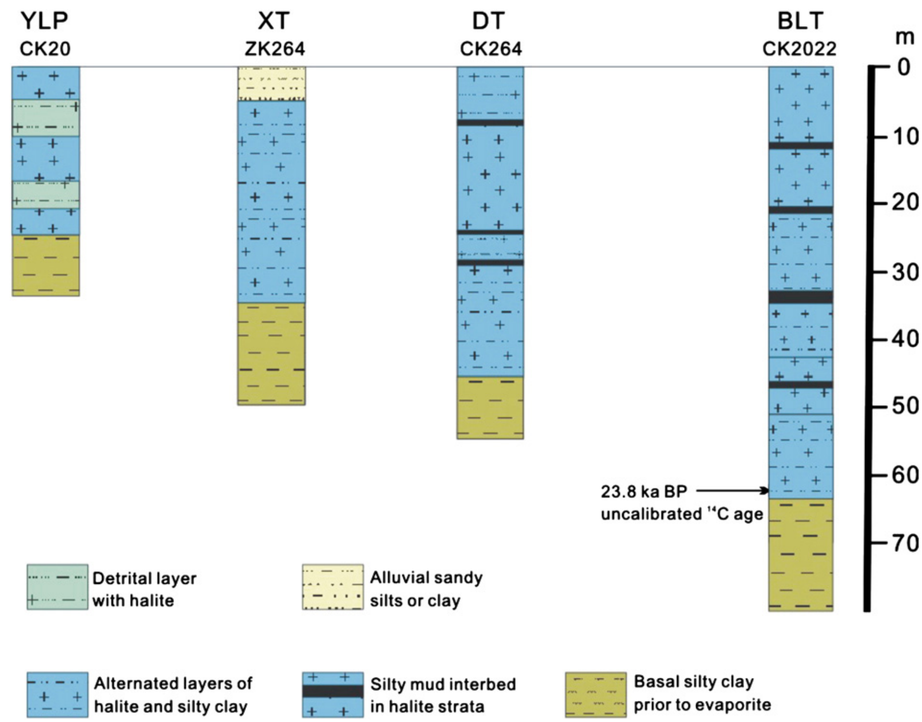

Fig. 13. Type cores of evaporite deposits from the four salt lakes of the BLT, DT, XT and YLP. Refer to Fig. 2 for location. Note that the elevation of the BLT today is 6 m lower than that of the DT, and it was about 20 m lower prior to the evaporite deposition. Data source of the cores: CK2022 after Huang et al. (1981); CK264 and CK20 after Cao and Wu (2004); ZK2016 after Zhang et al. (2002).

6. Conclusions

The hyperarid condition of the Qaidam Basin is determined primarily by the rain shadow effect as the basin is surrounded on all sides by high mountains. Our work provides the first case study showing that the topographically-induced differential effects of dry westerlies are the fundamental cause of contrasting hydroclimatic conditions between the wetter high-altitude mountains and hyperarid basins in the watershed of the Bieletan (BLT), DongTaijinaier (DT), XiTaijinaier (XT), and Yiliping (YLP). Such conditions are indeed essential for the formation of the halite-dominated evaporitic sequence and associated K^+-rich brine deposits in the study areas. Whether the Li^+-rich brines coexist with K^+-rich brine deposits depends on the distal supply of Li^+-rich thermal water via the Hongshui–Nalinggele (H–N) River, the largest river draining into the Qaidam Basin.

An annual discharge of 10.3×10^8 m^3 of the H–N River transports ~748.8 t of dissolved lithium per year into the Qaidam Basin. The river discharge, collected from the huge mountainous catchment of 20,790 km^2, increases greatly during two periods a year with peaked pulses between July and August. The massive seasonal inflows into the terminal basins result in immediate enlargement and dilution of the salt lakes, which is followed by rapidly shrinking lake size due to intense evaporation and the consequent enrichment of ions, such as Li^+ in the lake waters and related interstitial brines. Over the long-term this repeating process results in the formation of lithium-rich brine deposits in the four salt lakes of the BLT, DT, XT, and YLP, accounting for nearly 80% of the brine lithium found in China.

We found convincing evidence for a continuous supply of dissolved Li^+ for the salt lakes, which comes from the hydrothermal fields located near the upper reaches of the Hongshui River watershed. The hydrothermal fields are associated with a magmatic heat source. Our work reveals the fact that a subsurface rise between the BLT and DBX, formed before the evaporite deposition, blocked the passage of the inflows of Li^+-bearing water from the H–N River system. As a result, the lithium brine deposit is formed only in the BLT rather than in the entire Qarhan Playa. The reason that the lithium reserves of the BLT exceed the sum total of the DT, XT and YLP is attributable to the fact that during the progradation of the alluvial Fan I, the H–N River drained only into the BLT until the Taijinaier River (T-river) shifted watercourse to the north and began to feed the salt lakes of the DT, XT and YLP. Such a shift decreased the quantity of Li^+-bearing water draining to the Senie Lake and the BLT. The Wutumeiren (W-river) watershed today continues to provide Li^+-bearing water for the BLT salt lake, as the river runoff of more than 85% relies on groundwater discharge from the Fan I, which is associated with subsurface seepage of the H–N River water. This study identifies the significance of the geomorphic control associated with the evolution of two large alluvial fans on the depositional system of the four salt lakes.

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