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ORIGINAL ARTICLE

Boron isotope geochemistry of Bangor Co Salt Lake (central Tibet): implications for boron origin and uneven mixing of lake water

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Abstract
Boron is an essential, widely used, micronutrient element and is abundant in salt lakes on the Qinghai-Tibet Plateau. The origin and distribution of boron brine deposits on the Qinghai-Tibet Plateau is an important foundation for B resource formation, evolution, and enrichment, which have long been the subject of debate. The boron isotope system is a sensitive geochemical tracer, making it useful for effectively and precisely tracking a wide range of geological processes and sources. This study investigates the major cations, [B], and $\delta^{11}B$ values of samples (lake brine, river waters, and cold spring water) from the Bangor Co Lake which is a typical salt lake rich in boron in Tibet, China. There are magnitude-scale differences in [B] among different sample types: river samples < cold spring water << brine lakes. [B] values vary from 0.73 to ~1113 mg/L. Similar to [B], the $\delta^{11}B$ values of the samples exhibit magnitude-scale variations as [B], ranging from −7.35‰ to +7.66‰. There are also magnitude-scale differences in $\delta^{11}B$ among different sample types. The $\delta^{11}B$ values of cold spring water are relatively low, and the values range from −1.26‰ to -7.75‰. However, the river water samples and saline lakes have higher values, from 0.38‰ to 4.62‰, and the $\delta^{11}B$ values of river water samples are basically in the distribution range of those of Bangor Co Lake. This indicates that the sources of boron in Bangor Co Lake are mainly the recharge water with higher $\delta^{11}B$ values and spring water with lower $\delta^{11}B$ values, and the boron sources and the uneven mixing of lake water are two reasons that account for the large change in the $\delta^{11}B$ value of Bangor Co Lake.

Keywords Tibet · Bangor Co salt lake · Boron isotope · Origin · Fractionation processes

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1 Introduction

Tibet is China's largest salt lake concentration area. It is one of the plateau salt lake distribution areas with the most distributed, densest, and highest-elevation salt lakes in China (Zheng et al. 1983; Zheng and Liu 2010; Zheng 1988; Zheng and Yang 1981; Tang et al. 1981). There are approximately 234 salt lakes larger than 1 km^2. Half of them is rich in the resources of potassium, lithium, boron, etc.; thus the salt lakes in Tibet have important economic value and special status (Yu and Tang 1981; Zheng and Liu 2010; Liu and Zheng 2017). The boron resources in salt lakes are very abundant (Wu et al. 1984; Lin et al. 2017; Zheng and Liu 2010). At present, there are 108 salt lakes with B_2O_3 concentrations exceeding the industrial mining value, and the B_2O_3 resources are more than 47.68 million tons (Lin et al. 2017).

In the past decade, great attention has been given to boron resources in brine lakes in the Qaidam Basin and Tibet (Lin et al. 2017; Tan et al. 2012). Researchers have used B contents from different types of samples to explain the source of boron in brine lakes. These preliminary studies have not only an important reference value for the sustainable exploitation of boron deposits but also positive significance for deepening the study of salt formation and metallogenic regularity in salt lakes. However, much work is needed to systematically reveal the distribution and origin of boron brine deposits.

As one of the members of the “nontraditional stable isotope” family, boron isotopes have become a popular field and frontier of isotope geochemistry in recent years. Boron has two stable isotopes, ^{10}B and ^{11}B. The two isotopes have a large mass difference, which leads to considerable isotopic fractionation during various geological processes (Xiao et al. 2013, 2022). Therefore, boron isotopes are sensitive geochemical tracers that reflect the interactions between fluids and minerals from the surface to the mantle (Foster et al. 2010). Compared with B contents, boron isotopic composition ($\delta^{11}B$) provides an important approach to clarifying the genesis of deposits. Therefore, boron isotopes have been successfully used to constrain the origin of the boron-rich lake in the Qaidam Basin Xiao et al. 1992, 1999; Wei et al. 2014; Fan et al. 2015).

Lü et al. (2013) systematically studied the origin of boron in boron-rich salt lakes in Damxung Co Salt Lake in Tibet, showing that the origin of boron is controlled by carbonate clay. Bangor Co Lake, which is located in the central portion of Tibet, has solid boron deposits that occur in the lakebed and lakeside. It is one of the typical boron-rich salt lakes in Tibet, and it also represents the evolution process of the gradual concentration of Tibet salt lakes. Therefore, the characteristics of boron isotope fractionation of Bangor Co Lake were used to indicate the migration and enrichment process of boron.

In this study, brine salts, intercrystalline brine, river waters, cold spring water, borax crystals, and hydromagnesite were collected. Major cations, [B], and $\delta^{11}B$ values of the samples were analyzed. The aims of this study were to constrain the sources and distribution of boron brine deposits in Bangor Co Lake on the Tibetan Plateau, China, and to provide a scientific basis for studying the metallogenic regularity and mechanism of salt lake B resources.

2 Geological backgrounds

The Bangor Co Salt Lake is located in the southern part of the middle Bangong-Nujiang suture zone (BNSZ), displaced in one of the faulted basins in the BNSZ, which is an important tectonic zone in the Qinghai-Tibet Plateau (Fig. 1). Bangor Co is 8 km east of Siling Co and 75 km west of Bangor Country, Naqu area. Its elevation is 4522.5 m, and the lake area is approximately 130.6 km^2. Its annual average temperature is less than 1 °C, and precipitation is concentrated in the rainy season, from July to August. The other days of each year are dry, with annual precipitation of less than 150 mm and annual evaporation is of approximately 2200 ~ 2500 mm. This area belongs to the arid plateau boreal climate zone, and the water supply is mainly is atmospheric precipitation, springs, and rivers (Yin et al. 1994; Fang 2017; Erchie 2012; Wang et al. 2019).

Bangor Co is a lagoon of Siling Co and is separated from Siling Co, the largest lake in Tibet (Shi et al. 2017; Zhao et al. 2011). Bangor Lake is divided into three lakes by the natural formation of a hydromagnesite dam: Bangor Co I Lake, Bangor Co II Lake, and Bangor Co III Lake (Zheng et al. 2002). At the time of sampling, Bangor Co I was dry. Solid boron deposits mainly occur in the lakebed and lakeside of the Bangor Co II (Fig. 1). There are many small cold springs at the northern and southern ends of Bangor Co Lake. The main recharge river of Bangor Co is the Graza River, which flows into Bangor Co III Lake.

There are many sedimentary salt resources of salts in Bangor Co. Mirabilite, borate (borax), and hydromagnesite is industrial mined (Zheng et al. 2002). Mirabilite is distributed in the western of Bangor Co III Lake and buried at the bottom of Bangor Co II Lake; borate deposits are distributed in Bangor Co II Lake. Magnesite is distributed in the middle of lakes or around lakes to form lake embankments.

3 Sampling and analytical methods

3.1 Sampling

The river waters, cold spring waters, and Lake brines were collected in the winter of 2015 during one sampling expedition (Fig. 1). For the chemical analysis, all samples were filtered *in-situ* through 0.45 μm Whatman nylon filters. A sub-sample for cation analysis was collected into a polyethylene bottle precleaned with distilled HNO_3 and acidified to $pH < 2$. A second unacidified sample was collected for anion analysis. The temperature, pH, and density of the water samples were measured in the field using a portable meter. HCO_3^- was measured in the field by titration (Table 1).

A boron crystal sample was collected from the lakeshore east of Bangor Co (BG-19).

3.2 Major and trace element analyses

Boron crystal sample was treated following the method by Rattana et al. (2021). Solid sample was cleaned with ethanol and put in an air-dry oven (40 °C) for around 10–12 h and then was crushed to 200 mesh using an agate mortar. Then 2 ± 0.001 g of crushed sample were dissolved in 15 mL pure water, the solution samples were filtered *in-situ* through 0.2 μm Whatman nylon filters and diluted with pure water and 2% HNO_3 (10–30 times). The river waters, cold spring waters, and Lake brines were directly diluted. The Na^+, Mg^{2+}, K^+, Ca^{2+}, Cl^-, and SO_4^{2-} concentrations were

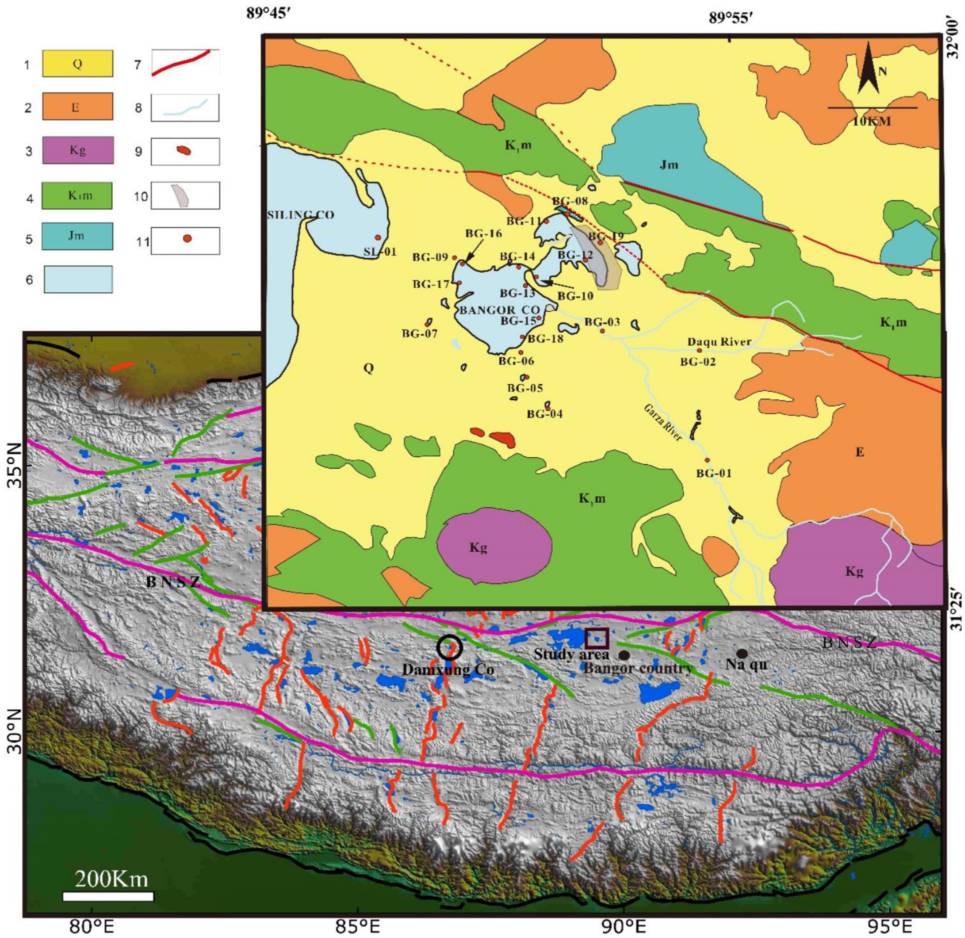

Fig. 1 Geological background and locations of samples in the Bangor Co Salt Lake (1. Quaternary; 2. Tertiary; 3. Cretaceous granite; 4. Cretaceous; 5. Jurassic; 6. Lake surface water; 7. Fault; 8. River; 9. Crenitic; 10. Solid boron deposit areas; 11. Samples)

determined at the Qinghai Institute of Salt Lakes (ISL), Chinese Academy of Sciences. All analyses for major ions in this study followed the procedures of the Qinghai Institute of Salt Lakes (He et al. 2020).

The B concentration of samples as was determined using an ICAP 6500 DUO ICP-OES at ISL.

To evaluate the long-term reproducibility of precision and accuracy of major and trace elements determinations, repeat measurements of the reference materials GBW-Li and seawater (NASS-6) were carried out. The analytical precision (RSD) $<3\%$ was achieved for major and trace elements determinations. All data are plotted in Table 2.

3.3 Boron chemical purification procedure

Pre-treatment method was for purification of B was carried out in an ultra-clean lab (100 class in an operating window) following the steps described by He et al. (He et al. 2016, 2019). Briefly, it was a one-step purification procedure for B and then an accurate and high-precision determination of its isotopic compositions by MC-ICP-MS. First, solute samples containing B about 300 ng were purified by single-step exchange chromatography filled up with 1.5 mL resin (Amberlite IRA 743 resin, 80–100 mesh), with 3 mL of 0.5 M HNO_3 as an eluent. The final B concentration was 100 µg/L for analysis.

The reference materials of NASS-6 and SRM951a were simultaneously purified for quality control requirements.

3.4 Measurements of B isotope ratios

All B isotope measurements were carried out at the State Key Laboratory of Loess and Quaternary Geology (SKLLQG), Institute of Earth Environment, Chinese Academy of Sciences (IEECAS) on a NEPTUNE Plus MC-ICP-MS, which enabled a static measurement of m/z 10 and m/z 11 on the low-mass Faraday cup (L4) and the high-mass Faraday cup (H4). A strong B memory effect requiring a long washout time is the big challenge of boron isotope measurements by MC-ICP-MS. He et al. found that acid NaF solution can be

Table 1 Field sample collection, description and measurement of temperature (T), Density and for the rivers, springs and lake brine

No.	Sample type	T (°C)	pH	Density	River discharge (m^3/s)	Description
BG-01	Graza river	7	8.4	1	1.23	The river before mixing
BG-02	Daqu river	9	8.4	1	0.2	Tributaries of the Graza river
BG-03	Graza River	15	8.9	1	1.40	The river after mixing
BG-04	Cold sping	13	8.0	1	Samll	Southern spring of Bangor Co
BG-05	Cold sping	5	7.9	0.97	Samll	Overflowing water of the BG-04 spring
BG-06	Cold sping	15	8.0	1	Samll	Overflowing water of the BG-04 spring
BG-07	Cold sping	16.5	8.1	1	Samll	Southern spring of Bangor Co
BG-08	Cold sping	13	8.0	1	Samll	Northern spring of Bangor Co, One of the bead-shaped distribution springs
BG-09	Cold sping	8	8.5	1	Samll	Northern spring of Bangor Co
BG-10	Lake brine	13	9.1	1.12	-	Bangor Co II Lake brine
BG-11	Lake brine	13	9.2	1.12	-	Bangor Co II Lake brine
BG-12	Lake brine	14	9.0	1.14	-	Bangor Co II Lake brine
BG-13	Lake brine	14	9.0	1.11	-	Bangor Co III Lake brine
BG-14	Lake brine	14	9.1	1.12	-	Bangor Co III Lake brine
BG-12	Lake brine	16	9.1	1.1	-	Bangor Co III Lake brine
BG-16	Lake brine	13	9.0	1.08	-	Bangor Co III Lake brine
BG-17	Lake brine	14	9.2	1.08	-	Bangor Co III Lake brine
BG-18	Lake brine	15	9	1.09	-	Bangor Co III Lake brine
BGS-19	Solid	-	-	1	-	Borax crystals
BGI-19	brine	12	9.2	1.16	-	Intercrystalline brine
SLM-01	Solid					hydromagnesite (new form)
SLM-02	Solid					hydromagnesite
Sl-01	Lake brine	12	8.6	1	-	Siling Co Lake brine

used to reduce boron signals to blank levels within 4 min. Therefore, acid NaF solution was used as a rinse solution (He et al. 2019).

To guarantee the precision and accuracy of the B isotopic analysis in this study. NASS-6 and SRM951a two reference materials were selected. The $\delta^{11}B$ values for NASS-6 and SRM951a were 39.36 ± 0.29 ‰ and 0.01 ± 0.32 ‰, respectively. All are in excellent agreement with previous studies (He et al. 2019).

4 Results

4.1 Hydrochemistry

The elemental results for the river water, salt lake, and cold spring water are shown in Table 2; Fig. 2. the different sample types exhibit different characteristics.

River water is dominated by Ca-Mg-HCO_3^- or Mg-Ca-HCO_3^- types. The cold spring water located the south of Bangor Co shows a Ca-Mg-HCO_3^- or Mg-Ca-HCO_3^-; the overflowing cold spring (BG-04), which is near Bangor Co Lake, shows a Na-Cl^-- HCO_3^- type; and the cold spring water located in the north of Bangor Co shows a Na-SO_4^{2-} type. However, the salt lake samples show that Na^+ and Cl^- are the dominant major ions, and the water type is Na-SO_4^{2-}.

The Ca^{2+} content in the lake water is generally lower than or equivalent to that in the river water and cold spring water samples, except for BG-14 in the northern part of Bangor Co. The content of Mg^{2+} is approximately ten times higher than that of Ca^{2+}.

Bangor Co Salt Lake is famous for its boron resources and is rich in lithium and potassium. Lithium, potassium, and boron are high in lake water and are more than 100 times more enriched than in river water or cold spring water. The B/Li ratios in the lake water are generally consistent. The [B] of Selin Co Lake water is lower than that of Bangor Co.

The Gibbs diagram is an effective method to analyze the effects of regional evaporation-concentration, rock weathering, leaching, and precipitation processes on the water chemistry of surface water (Gibbs 1970; Gaillardet et al. 1999; Li et al. 2015). The Gibbs diagram of this study is plotted in Fig. 3. The river water samples are mainly affected by rock weathering and evaporative crystallization from the Na/(Na + Ca)-TDS diagrams. The weathering of rocks and evaporative crystallization provides a rich source for lake water. There are large evaporative deposits in the upper reaches of the river from the Google Earth map.

Table 2 Water chemical data of the river water springs, lake brine and solid boron ore in Bangor Co area

No.	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	CO_3^{2-}	HCO_3^-	SO_4^{2-}	B	Li	TDS	$\delta^{11}B$
						mg/L						(mean ± 2 SD ‰)
BG-01	34.7	5.3	33.6	19.6	6.0	0	213.8	35.3	0.8	0.06	353.6	4.62 ± 0.25
BG-02	40.3	4.9	35.7	23.3	9.4	0	233.6	49.1	0.9	0.09	400.5	-0.52 ± 0.52
BG-03	23.2	6.0	37.9	41.1	4.9	0	342.7	20.3	1.1	0.13	504.7	2.93 ± 0.18
BG-04	27.4	7.3	57.0	20.0	28.3	0	193.9	70.7	0.7	3.05	439.1	-7.35 ± 0.40
BG-05	63.0	10.0	36.7	30.2	18.3	19.51	253.4	68.2	0.8	0.08	487.4	-3.30 ± 0.17
BG-06	1128.0	174.6	6.5	93.0	841.3	390.2	967.1	1133.0	20.7	0.05	4802.8	-1.26 ± 0.17
BG-07	59.2	14.8	77.4	68.6	39.8	0	628.9	28.8	1.1	0.26	925.1	-5.96 ± 0.32
BG-08	407.3	45.4	12.2	65.9	255.2	39.51	495.5	442.3	17.1	0.93	1789.0	-0.04 ± 0.19
BG-09	86.9	22.4	46.3	49.6	36.5	0	555.5	308.0	16.3	0.51	1122.0	7.66 ± 0.19
BG-10	78420.0	7949.0	27.1	459.1	22169.0	6841.0	7675.0	108100.0	876.0	141.30	234635.0	0.38 ± 0.18
BG-11	75080.0	9698.0	22.2	535.5	27495.0	8414.0	9063.0	84330.0	1052.0	175.40	218204.1	1.48 ± 0.26
BG-12	95140.0	10730.0	37.3	528.0	28438.0	9719.0	8840.0	123600.0	1028.0	162.80	280817.2	0.59 ± 0.17
BG-13	73430.0	9370.0	26.4	522.9	27270.0	8389.0	9820.0	83760.0	1049.0	180.70	216167.1	0.54 ± 0.37
BG-14	69030.0	8152.0	373.0	464.9	22259.0	6829.0	7638.0	87390.0	883.0	147.20	205099.1	0.56 ± 0.32
BG-12	68050.0	8501.0	32.5	396.6	24778.0	8231.0	9113.0	77570.0	1113.0	198.10	200148.2	3.59 ± 0.26
BG-16	58990.0	7137.0	49.3	453.7	20678.0	6097.0	6931.0	68530.0	822.0	140.70	171657.7	1.45 ± 0.25
BG-17	56290.0	6941.0	25.6	431.0	20017.0	5756.0	6794.0	66540.0	817.0	125.20	165554.2	1.07 ± 0.19
BG-18	58880.0	6961.0	30.2	440.4	20735.0	6231.0	6943.0	69660.0	824.0	125.90	172662.2	1.29 ± 0.15
BGI	-	-	-	-	-	-	-	-	-		95203.3	3.44 (Qi et al.,1993)
BGS-19	-	-	-	-	-	-	-	-	-		-	-3.75 ± 0.10
BGI-19	96328.0	17210.0	35.2	528.0	29732.0	9827.0	8840.0	101620.0	1313.0	192.30	293217.4	-3.59 ± 0.15
SLM-01									160.0	100.00		-1.97 ± 0.16
SLM-02									100.0	44.00		2.79 ± 0.05
Sl-01	2681.0	317.0	5.5	158.6	1931.0	510.9	0	3168.0	186.2	8.61	8966.6	0.10 ± 0.22

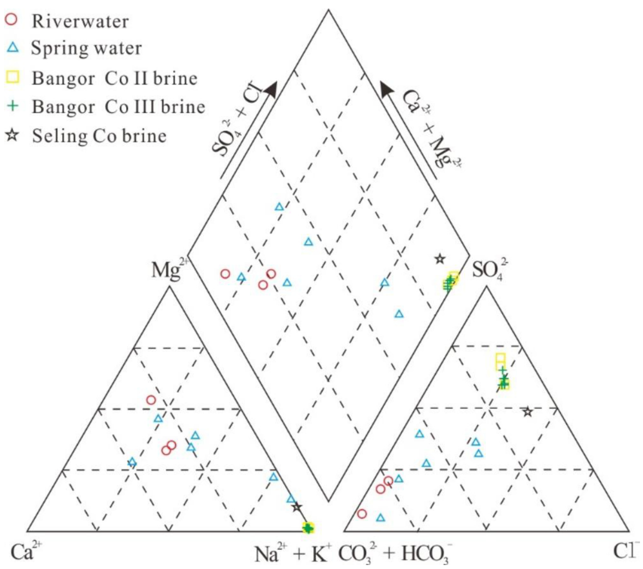

Fig. 2 Piper plot showing the chemical variability of selected samples

Except for BG-09 and BG-06, most spring water samples are also affected by rock weathering and evaporative crystallization, similar to the river water samples. BG-09 and BG-06 have the characteristics of low calcium and high bicarbonate content from $Cl/(Cl+HCO_3^-)$-TDS. This kind of water is mainly distributed in arid areas with strong evaporation and is controlled by the effect of evaporation.

4.2 Boron content and boron isotopic composition

The B content and $\delta^{11}B$ values of samples for the rivers, springs, and lake brine display magnitude variation. The B content varied from 0.75 to 1113 mg/L. The B contents of spring water and river water are relatively low, ranging from 0.75 to 20.68 mg/L. However, saline lakes have higher values, and the B content is as high as 1113 mg/L. The $\delta^{11}B$ values vary from −7.35‰ to +7.66‰ (Table 2). The cold spring samples the south of the lake have lighter $\delta^{11}B$ values, ranging from −1.26‰ to −7.75‰. However, cold spring water the northwest of the lake has $\delta^{11}B$ values of 7.66‰. The $\delta^{11}B$ values of lake brine fluctuate in a small range, ranging from 0.38‰ to 3.59‰.

Boron crystal samples were collected from the lakeshore east of Bangor Co (BG-19), and the $\delta^{11}B$ value is −3.75, which is lower than that of the lake water (Table 2).

5 Discussion

5.1 Calculated amount of boron resources input into salt lakes by rivers

The Graza River is the main recharge river input for Bangor Co Lake. The total amount of B input to the lake by the

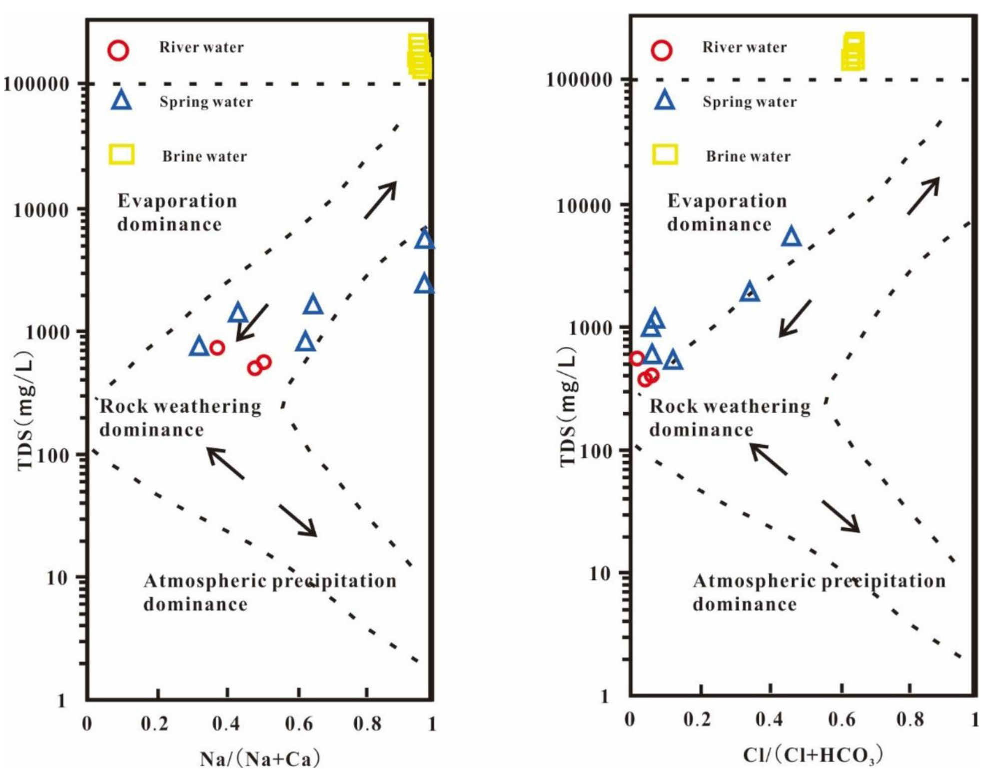

Fig. 3 Gibbs diagram of recharge water of Bangor Co lake

Graza River water can be calculated based on the water-salt balance. The equation is given by:

$$\sum W = S \times C \times 10^{-6}$$

where ΣW is the annual total amount of B input into Bangor Co Lake by the rivers in tons and S is the flux of river water. C is the annual concentration of B in the river water. The average flow velocity of the Garza River is approximately 1.4 m^3/s, and the B content is approximately 1.14 mg/L. The calculated results show that the annual total B input into Bangor Co Lake by the Graza River is approximately 116 tons. The time of river recharge to the salt lake is no more than 19 thousand years (Shi et al. 2015; Zhao et al. 2018). Thus, the total amount of B from the Garza River is estimated to be at 1.76 million tons.

The total amount of boron resources in the whole Bangor Co region is more than 3 million tons. The amount of solid boron ore is greater than 1.1 million tons (Fan 1959). The solid resources are mainly located at the bottom and the shore of Lake Bangor Lake II (Fig. 1). In contrast to the 3 million tons, it is obvious that the recharge of the river is not sufficient. Thus, in addition to the river supply, there may be other sources supplying boron to Bangor Co Lake.

5.2 Distribution characteristics of B content and $\delta^{11}B$ values within the watershed of Bangor Co Lake

There is one river and some cold spring water around the Bangor Co Lake. All of them exhibit different B contents and $\delta^{11}B$ characteristics. The Graza River is the main recharge river of Bangor Co. The Daqu River is a tributary of the Graza River. The B contents of the upper reaches of the Graza River (BG-01) and the Daqu River (BG-02) are almost the same, with values of 0.8 and 0.9 mg/L, respectively. The B content after river mixing is 1.1 mg/L (BG-03) (Fig. 4; Table 2). The elevated boron content may be related to the evaporation of the river water. The cold springs that are far away from the Bangor Co Lake have a low B content that is close to that of the river water (BG-04, BG-05, and BG-07). However, the springs that are close to Bangor Co Lake vehad a higher B content. The $\delta^{11}B$ values of Graza River (BG-01 and BG-03) are 4.62‰ and 2.93‰, respectively. The $\delta^{11}B$ value of the Daqu River is -0.52‰. A large amount of hydromagnesite was deposited in the Bangor Co Lake, which can be found around the BG-06. Therefore, BG-09 and BG-06 two samples are likely to leach the hydromagnesite deposited formed in the early period.

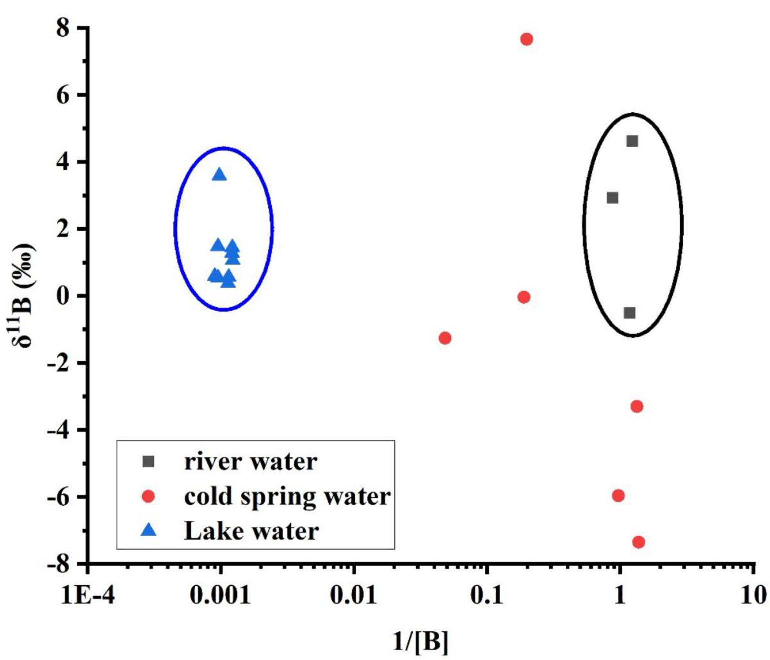

Fig. 4 The relationship between $\delta^{11}B$ and 1/[B] of different samples

5.3 Boron isotope geochemistry of Bangor Co Salt Lake

The boron concentrations from lake water are very high, with values of 817–1113 mg/L (Fig. 4; Table 2). The boron contents of Bangor II Lake and III Lake are different. The boron content of Bangor II Lake (BG-10, BG-11, and BG-12) is higher than that of Bangor III Lake (BG-13, BG-14, BG-15, BG-16, BG-17, and BG-18). The B content of Bangor II Lake varies from 876 to 1052 mg/L, with an average of 985 mg/L. The B content of Bangor III lake varies from 817 to 1113 mg/L, with an average of 918 mg/L. The δ^{11}B values of Bangor lakes have a little variation, between 0.38‰ and 3.59‰ (Table 2). The δ^{11}B values of the Bangor III Lake are in the range of 1.07 to 3.59 ‰, while those of Bangor II Lake in Bangor are slightly lower, 0.38–1.48 ‰.

5.4 Influence of sedimentary minerals on the boron isotopic composition of Bangor Co Lake

There are many sedimentary minerals, such as borate (borax), mirabilite, and hydromagnesite in Bangor Co Lake (Zheng et al. 2002).

Borate precipitation experiments were carried out by Oi et al. under different pH conditions (7.35–11.54) (Oi et al. 1991). The results showed that the fractionation factor of borax and solution is 1 at pH = 9.5. As shown in Tables 1 and 2, the pH of intercrystalline brine (BGI-19) is exactly 9.2. The δ^{11}B values of intercrystalline brine and borate crystals are −3.59 ± 0.15‰ and −3.75 ± 0.10‰, respectively. The fractionation coefficient in this study is 0.998 at pH = 9.2. This value was consistent with $^{11-10}K_B$ calculated theoretically using Ab-initio molecular orbital theory (Oi 2000). This result indicates that there is no isotopic fractionation during the evolution of salt precipitation in Bangor Co.

Natural evaporation experiments of salt lake brine were carried out by Sun et al. (1993). The results showed that the boron isotopic composition of brine did not change. As shown in Table 2, the δ^{11}B values of the two hydromagnesite samples are − 1.97 ± 0.16‰ and 2.79 ± 0.05‰, respectively. The difference in boron isotopic composition between the hydromagnesite and lake surface brine and intercrystalline brine is also very small.

Therefore, there is no isotopic fractionation during the evolution of salt precipitation in Bangor Co.

5.5 The factors controlling the difference of δ^{11}B values of Bangor Co Lake

There may be two reasons that account for the large change in the δ^{11}B value of Bangor Co Lake the boron isotopic composition of the brine during the salt deposition. One is that there are two or more boron sources for Bangor Co Lake; the other is the uneven mixing of Lake water due to a great increase in lake water in recent years.

5.5.1 Potential sources of boron in the Bangor Co Lake

Considering that the boron source should have a certain boron content, there are two main boron sources for Bangor Co Lake. One is recharge water with higher δ^{11}B values, such as the Graza River (BG-01, 4.62‰) and spring water (BG-09, 7.66‰), and the other is spring water with lower δ^{11}B values (BG-04 and BG-07, −7.35‰ and −5.96‰). Spring water with lower δ^{11}B values has a great influence on the boron isotopic composition of Bangor Co Lake.

The lake brines collected in this study are all newly formed lake waters. Therefore, they cannot represent the δ^{11}B values of brines in salt lakes in the later stage of evolution. As mentioned above, the existing abundant salt deposits do not cause significant changes in the δ^{11}B value of the Bangor Co brine. On the one hand, it shows that the recharge of surface water (BG-02), which is characterized by the leaching of early lacustrine sediments, is unlikely to cause large fluctuations in the δ^{11}B value of the brine. On the other hand, intercrystalline brine (BGI-19) can represent the δ^{11}B characteristics of the original Bangor Co brine (the later stage of evolution).

The element molar ratio was used as a parameter to eliminate the influence of the enrichment process because the evolution of the salt lake will cause a sharp enrichment of soluble elements. The B/Cl molar ratios were calculated from Table 2. The relationship between the B/Cl molar ratio and δ^{11}B is plotted in Fig. 5. Binary mixed simulation calculations were also performed, as shown in Fig. 5. If the intercrystalline brine (BGI-19) is considered representative of the original Bangor Co brine, the recharge from the spring with lower δ^{11}B values during the evolution of Bangor Co is greater than 90%. If the existing lake surface brine samples are considered representative of the newly formed lake water, except for BG-15 (δ^{11}B = 3.59‰), most of the newly formed lake water is also more than 60% affected by this spring water with low δ^{11}B values.

5.5.2 Uneven mixing of Bangor Co Lake water

Zhao et al. (2011) conducted a detailed investigation of geomorphology and Quaternary geology along the bank of Bangor Co Lake, which included a leveling survey of lake level elevations, and the measurement of lake terrace heights along with six profiles and the collection of lake deposit samples for U-series dating. The results showed that from 1959 to 2003, the lake surface of the Bangor Co was overall rising, reaching up to 1.75 m. In contrast, from 1959

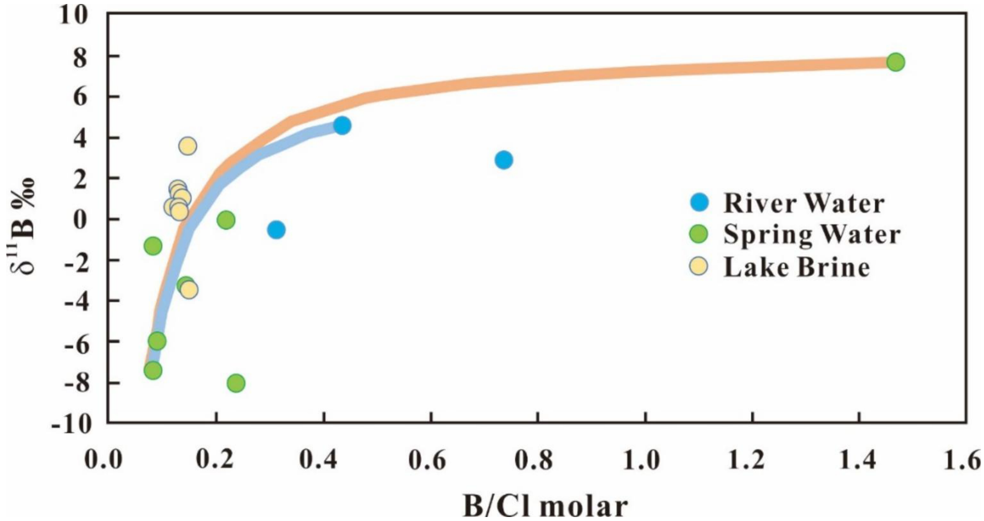

Fig. 5 The relationship between B/Cl molar and $\delta^{11}B$, and binary mixed simulation calculations

to 1973 or slightly later, there occurred a process of first falling, then rising, and again slightly falling, with a fall of 0.25 m, and an accompanying contraction of the lake area. Compared with the original water level, it can be found that the sampling sites of this study are located on the periphery of Bangor Lakes II and III before the year 1973, which both formed after the rise of Bangor Co Lake in the past two decades. In recent decades, with global warming, river recharge has increased. The lake surface has expanded, and the newly formed lakes have been affected by recharge water with a certain high $\delta^{11}B$ value, such as water from the Graza River. At the same time, the new lake water also dissolves and filters local lacustrine deposits and mixes with residual brine. However, affected by the geometry of the lake bottom topography, the mixing degree of the newly formed lake water is very low, which shows that the boron isotopic composition of the lake surface brine varies greatly.

6 Conclusions

The [B] and $\delta^{11}B$ values of the brine salts in the Bangor Co Lake on the Tibetan Plateau, China, are determined. Our main conclusions are as follows:

(1) There are magnitude-scale differences in [B] among different sample types: river samples < cold spring water << brine lakes. The [B] values vary from 0.73 to ~1113 mg/L.

(2) similar to [B], the $\delta^{11}B$ values of the samples exhibit as magnitude-scale variations as [B], ranging from −7.35‰ to +7.66‰. There are also magnitude-scale differences in $\delta^{11}B$ values among different sample types.

(3) The sources of boron in Bangor Co Lake are mainly the recharge water with higher $\delta^{11}B$ values and spring water with lower $\delta^{11}B$ values.

(4) The boron sources and the uneven mixing of lake water are two reasons that account for the large variation in the $\delta^{11}B$ value of Bangor Co Lake.

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Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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