Hydroclimatic and geothermal controls of lithium brine deposits on the Qinghai-Tibetan Plateau

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Abstract. The paper focused on the distribution characteristic, material source and ore-forming mechanism of lithium brine deposits on the Qinghai-Tibetan Plateau, and established the lithium brine deposit model. The results showed that all lithium brine deposits are controlled by the Neotectonics, enclosed/semi-enclosed low catchment basin and hyper-arid climate conditions, and related to the Cenozoic hydrothermal activities. The ore-forming materials especially lithium element are derived from volcanic rocks, which migrated and concentrated after water-rock interaction by hydrothermal springs and atmospheric precipitation.

1. Introduction

The lithium brine deposits are mainly found in the surface brine, intercrystalline brine and pore brine, with the characteristics of abundant reserves and extremely uneven distributions. Salt lakes in Qaidam Basin on the Qinghai-Tibetan Plateau contained 2.3 million tons lithium, most of which were reserved in Bieletan (BLT), Dong Taijinaier (DT), Xi Taijinaier (XT) and Yiliping (YLP), accounting for nearly 80% brine lithium found in China [1]. Here we report the formation process and distribution pattern of lithium brine deposits on the Qinghai-Tibetan Plateau, aiming to demonstrate the formation controlled by the hydroclimatic conditions, geomorphology and the sources. The results from this study are anticipated to be useful for the sustainable exploitation and ore-forming theory of lithium brine deposits in the salt-lake system.

2. The distribution of lithium brine deposits

From southern to northern Qinghai-Tibetan Plateau, the hydrochemical type changed from carbonate type to sulfate type and chloride type under the gradually strengthened arid climate. The average brine lithium content in Qaidam Basin, Hoh Xil and Tibet is 67.8 mg/L, 73.7 mg/L and 264.0 mg/L, respectively. Thus it can be seen that the brine lithium content of salt lakes on the Qinghai-Tibetan Plateau increased gradually from Qaidam Basin to Tibet. As shown in figure 1, several super-large lithium brine deposits existed in Tibet. Hoh Xil and Qaidam Basin. Two lithium brine deposits existed in the western (between Shiquan River and Cuoqin County) and northern (Nima County) of Tibet, with the lithium content exceeding 500 mg/L and 300 mg/L, respectively. Two lithium brine deposits were found in Lexiewudan and Xijinwulan Salt Lake of Hoh Xil[2], with all the lithium contents...
more than 100 mg/L, and Lexiewudan Lake is confirmed to be a chloride-type lithium brine deposit[2]. Four salt lakes including YLP, XT, DT and BLT in the central of Qaidam Basin as well as Da Qaidam Salt Lake existed in the northern Qaidam Basin, with the lithium content exceeding 125 mg/L and 100 mg/L, respectively (Table 1). Especially, due to the extremely low Mg/Li ratio (only 0.01) and simpler extraction process, Zhabuye salt lake is one of the few high-quality lithium brine deposits in the world. However, due to the influence of climate change in recent years, some salt lakes on the Qinghai-Tibetan Plateau have shown different degrees of water desalination with decreasing grade of brine lithium. In addition, the Li⁺-bearing salt lakes are associated with potassium, boron, magnesium, sodium, calcium, rubidium, cesium and bromine, especially high Mg/Li ratio found in salt lakes enriched in lithium from Qinghai (Table 1), which caused the lithium extraction from lake brine is very difficult.

Table 1. The basic data of important lithium brine deposits on the Qinghai-Tibetan Plateau [2-5].

| Salt lake        | Lithium (mg/L) | Mg/Li ratio | Water type | Reserves (10⁵ tons) |
|------------------|----------------|-------------|------------|--------------------|
| Zhabuye lake     | 632            | 0.01        | SC         | 153.0              |
| Zhacang Chaka    | 807            | 10.30       | MS         | 2.8                |
| Bange Co         | 247            | 0.04        | MC         | 3.1                |
| Dangxiong Co     | 211            | 0.22        | MC         | 17.0               |
| Mami Co          | 91             | 4.11        | NS         | 39.5               |
| Bieletan Playa   | 191            | 0.06        | MS         | 126.7              |
| Dong Taijinaier Lake | 300            | 40.32       | MS         | 46.6               |
| Xi Taijinaier Lake | 220            | 65.57       | MS         | 50.4               |
| Yiliping Playa   | 210            | 92.30       | MS         | 29.2               |
| Da Qaidam Lake   | 127            | 65.00       | MS         | 6.3                |
| Lexiewudan Lake  | 171            | 12800       | Ch         | 5.9                |
| Xijinwulan Lake  | 101            | 24600       | MS         | 16.5               |

* MS—magnesium sulfate.
  b NS—sodium sulfate.
  c SC—strong carbonate.
  d MC—medium carbonate.
  e Ch—chloride.

Figure 1. The distribution of main lithium brine resources on the Qinghai-Tibetan Plateau (modified after Zhao [6]).
3. The source of lithium brine deposits

Geothermal water is widely distributed on Qinghai-Tibetan Plateau[7-8], where more than 600 thermal spring spots/groups are found, with some mud volcanic water. Elements such as lithium, boron, rubidium and cesium in lake brine from Tibetan Plateau are derived from anatectic magma, and thermal springs are the main carrier for importing into salt lakes [9-12]. In particular, 595 tons Li⁺ and 5370 tons B₂O₃ from the thermal springs imported into the lakes in southern Qiangtang-Himalayan region every year, which is enough to form lithium and boron deposits in modern salt lakes on Tibetan Plateau[13]. It should be pointed out that Zhabuye Salt Lake experienced a “pan-lake” period in the Late Pleistocene, with a large amount of ore-forming materials such as boron and lithium. The Miocene boron and lithium-bearing volcanic deposits have been found in catchment basin, which is an important material source of boron and lithium deposits in Zhabuye [14]. In addition, the boron and lithium contents in strata of Zhabuye is relatively lower, but migrated and enriched in the lake via river waters after the long-term weathering and leaching, which is another potential source of boron and lithium deposits in Zhabuye [14]. Therefore, the geothermal spring waters may be the main source of evaporite deposition in salt lakes of Tibet.

Three different hypotheses on the origin and source of lithium brine deposits in the central of Qaidam Basin were drawn as follows: a) a substantial contribution of lithium was from residual brine formed in the western Qaidam Basin during the latest Pliocene, which migrated eastward due to the basin’s tectonic tilting and entered the Qarhan playa via the salt lakes of YLP, XT and DT, the residual brine interacted with the Li⁺-rich waters of other possible sources such as that from deep underground connate brine of Tertiary age, which facilitated the enrichment of lithium in salt lakes since Late Pleistocene[15]; b) the important contributions of lithium from “Nalenggele paleolake” and “Kunlun paleoake”, which possibly existed as large intermontane lakes in Kunlun Shan until 30 ka BP, the tectonic-induced drainage into the Qaidam Basin of these two “ancient saline lakes”, several others within the eastern Kunlun Shan was thought to be a primary cause of the commencement of evaporite deposition, and ultimately the source of lithium, boron and potassium in Qarhan playa[16]; c) the lithium-bearing thermal spring waters in Kunlun Shan recharged into the four salt lakes via the Hongshui-Nalenggele River, but the weathering and erosion of volcanics contributed less to Hongshui-Nalenggele River[1]. As Da Qaidam Salt Lake in the northern Qaidam Basin, the lithium-bearing thermal spring waters from Wenquangou region recharged into lake with the lithium content is about 3 mg/L.

In summary, the understanding on potential sources of lithium brine deposit as follows: a) the lithium-bearing thermal springs in the adjacent volcano; b) the weathering and leaching of lithium-bearing surrounding rocks; c) the upwelling of brine lithium along the deep fault and mixing with the salt-lake brine.

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Figure 2. The red star indicated the location of a hydrothermal field lying at the foot of Bukadaban Shan and in the area where two active faults of the Kunlun Fault converged, and the hydrothermal spring enriched in lithium eject from 150 vents, forming a lake from which drains into Hongshui River.

4. Formation processes and distribution pattern

4.1. Formation processes

In this study, we focused on the four salt lakes including YLP, XT, DT and BLT in the central of Qaidam Basin. Recent study found that, the hydrothermal field in the Hongshui River valley is
particularly developed controlled by the Neotectonic movement of Kunlun Fault and frequent earthquakes, and a large amount of lithium-bearing thermal spring water ($\text{Li}^+ 96 \text{ mg/L} \ [17]$) gushed out, which is the main lithium source of Hongshui River. The thermal spring groups are located at Bukadaban Shan, where the average annual precipitation exceeding 260 mm, together with the melt water in summer, which is conducive to the recharge of surface water. There is up to a 2200 m difference between the upstream of Hongshui River and the four salt lakes in the central of Qaidam Basin. The Hongshui River valley cut through Kunlun Mountain, and continuously provided the water enriched in lithium to the salt lakes of Qaidam Basin. Under the hyper-arid climate conditions, the lithium brine deposits formed by evaporation and concentration effects. In other words, the differential effect of climate warming condition between the high mountain catchments and arid basin is the key factor for evaporite deposition and lithium brine deposit. Moreover, the formation of paragenetic lithium brine deposits entirely depend on the recharge of high lithium-bearing river water. Compared to Golmud River, the lithium content in Hongshui-Nalenggele river system is more than 20 times, and the runoff is also much higher. The high lithium-bearing water via Utumeiren River flowed into Senie Salt Lake and Beletan playa, which caused that the lithium brine deposit was only formed in Beletan zone at the western end of Qarhan playa. Nevertheless, the underground uplift blocks lithium-bearing water flowing into the eastern, resulting in the lithium brine deposit in Dabuxun zone as well as the eastern zone are not formed [1].

It should be noted that the differential effect above-mentioned will be enhanced in warm period, so that the Early to Middle Holocene warm period was more favorable to a large amount of evaporite deposition formed in Qarhan playa, rather than Last Glacial period (24-25 ka BP) [18-19]. This is because the increasing surface temperature in the relatively warm period, which caused the intensifying vertical convection under the condensation in mountainous terrain, and resulted in increasing precipitation in Kunlun Shan and accordingly increasing runoff into the salt lakes of Qaidam Basin. The Qarhan playa can be covered seasonally, and the evaporation in Qaidam Basin enhanced, which was more favorable to evaporite deposition.

4.2. Ore-forming model
In the early geological period, catchment basin was the deposition center, where evaporite deposition formed with brine lithium enriched. Later, the paleo-lake in catchment basin began to directional migration due to tectonic uplift, and finally formed a closed lake basin. Meanwhile, the subsidence caused by fault activity in the basin provided a high brine permeability, the geographical drop between mountain catchments and arid basin, as well as the rain shadow effect caused extremely arid climate conditions in basin. The seasonal rivers from mountain catchments recharged into the lake under the strong evaporation and concentration effects, which is an important climate condition for the lithium brine deposit. Finally, the magmatic hydrothermal fluids, lithium-bearing surrounding rocks and volcanic ejecta caused by the Cenozoic volcanic activities around catchment basin, providing a different potential sources of brine lithium. Under the control of long-term geological process and extremely arid climate conditions, the $\text{Li}^+$ concentrated and enriched continuously, and the lithium brine deposit in salt lakes are formed (figure 3).
5. Conclusions

The brine lithium in salt lakes are important strategic resources in China, and the lithium-bearing salt lake groups are mainly on the Qinghai-Tibetan Plateau. However, the lithium extraction technology and engineering research have been paid much attention in recent years, with lacking understanding of the origin and distribution pattern of lithium brine deposits, which is related to the serious loss of lithium resources. Our results showed that lithium brine deposits are controlled by Neotectonic movement and closed/semi-closed low-lying catchment basin as well as the extremely arid climate conditions. All lithium brine deposits are related to the Cenozoic geothermal activity, the ore-forming materials especially lithium is mainly derived from eruptive rocks, then migrated and concentrated via the thermal springs and atmospheric precipitation. Under the control of long-term geological process and extremely arid climate conditions, the Li$^+$ concentrated and enriched continuously, and the lithium brine deposit in salt lakes are finally formed.

Acknowledgments

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