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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%.