The Impact of the Linked Factors of Provenance, Tectonics and Climate on Potash Formation: An Example from the Potash Deposits of Lop Nur Depression in Tarim Basin, Xinjiang, Western China

LIU Chenglin1,2,*, JIAO Pengcheng1, LÜ Fenglin1,2, WANG Yongzhi3, SUN Xiaohong1, ZHANG Hua1, WANG Licheng1 and YAO Fojun1

1 MLR Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China
2 School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China
3 College of Instrumentation & Electrical Engineering, Jilin University, Changchun 130061, China

Abstract: Potash deposits commonly accumulate in highly restricted settings at the final stage of brine evaporation. This does not mean that potash deposits are formed simply as a result of the evaporation concentration of seawater or lake water, but rather as a coupling result of particular provenance, tectonics and climate activities. In this paper, we focus on the formative mechanism of the potash deposits of Lop Nur depression in Tarim Basin to interpret the detailed coupling mechanism among provenance, tectonics and climate. In terms of the provenance of Lop Nur Lake, the water of the Tarim River which displays “potassium-rich” characteristics play an important role. In addition, the Pliocene and Lower-Middle Pleistocene clastic beds surrounding Lop Nur Lake host a certain amount of soluble potassium and thus serves as “source beds” for potash formation. During the late Pliocene, the Lop Nur region has declined and evolved into a great lake from the previous piedmont and diluvial fan area. Since the mid Pleistocene, the great-united Lop Nur Lake has been separated and has generated a chain system consisting of Taitema Lake, Big Ear Lake and Luobel Lake which has turned into the deepest sag in Lop Nur Lake. Dry climate in Lop Nur region has increased since the Pliocene, and became extreme at the late Pleistocene. The study implies that potash formation in Lop Nur Lake depends on the optimal combination of extreme components of provenance, tectonics and climate during a shorter-term period. The optimal patterns of three factors are generally characterized by the long-term accumulation and preliminary enrichment of potassium, the occurrence of the deepest sub-depression and the appearance of an extremely arid climate in Lop Nur region. These factors have been interacting synergistically since the forming of the saline lake and in the later stages strong “vapor extraction” caused by extremely arid climate is needed to trigger large scale mineralization of potash deposits.

Key words: Potash formation, coupling mechanism, provenance, tectonics, climate, Lop Nur, Tarim basin

1 Introduction

Potash deposits are chemical precipitation products of seawater or lake water within closed or semi-closed regions (basins) on Earth’s surface at the final stage of brine evaporation and concentration under arid climates. The formation of potash deposits is dependent on key factors of appropriate provenance, accommodation space (i.e. the presence of a tectonic depression or sag) and an extremely arid climate (Schmalz, 1969; Warren, 2010).

* Corresponding author. E-mail: liuchengl263.net

Each of these factors is indispensable and only the best configuration of the three can form potash deposits. Usiglio (1849) first revealed mineral-crystallizing sequences of seawater during evaporation and concentration (i.e. process of potash deposition): iron oxide + calcium carbonate → gypsum → gypsum + halite → gypsum + halite + epsomite + gypsum + halite + epsomite + picromerite → gypsum + halite + epsomite + picromerite + carnallite, and proved that potash deposition occurred in the final phase of this process. Ochsenius (1877) was the first to introduce the “sand bar” theory, proposing that
concentration of seawater and formation of salt minerals should often happen within areas isolated by sand spits. Vaydashko (1965) proposed that potash formation is associated with the preparatory basin and formed in playa environments. That means before potash formed, seawater had been concentrated in a preparatory basin, and when potassium minerals started to precipitate, salty lakes in marine basins should have evolved into a playa phase. Borchert and Muir (1964) proposed the “multi-subbasins” sedimentary model for marine evaporite deposits. Schmalz (1969, 1970) reported a “deepwater” model assuming that evaporites formed in deep-water environments and proposed the two distribution models for evaporites, i.e. the “Bull’s eye” model and the “Tear drop” model. Hsu (1972) believed that in the case of the Mediterranean, the fact that the inland sea has been dried up to form very thick salt deposits is attributable to Messinian Salinity Crisis in the Mediterranean, and thus proposed a “desiccated deep basin” model to account for the origin of saline giants.

In China, many important discoveries have been reported from the continental genesis models, based on an understanding of salt and potash formation in specific local geological settings, including: “high mountain-deep basin” salt formation model (Yuan et al., 1983), the “multi-stage basin” salt formation model (Zheng et al., 1989), and the “high mountain-deep basin oscillation-drying, separated basin synchronous differentiation” potash formation model (Zhang, 1987). The formations of some large potash deposits are strongly associated with brine alimentation originating from the deep in basins mainly by ascending springs (Qu, 1982; Lowenstein et al., 1988). Based on potash genesis studies on the Lop Nur saline lake, Wang et al. (2005) proposed the “high mountain-deep basin, tectonic migration” model and a “two-stage potash formation” model. Liu et al. (1996, 2013a) suggested an “inverse lake-chain” model for salt formation and a rifting-potash formation model, etc. These models highlighted critical factors of coupling of provenance, tectonics and climatic conditions for potash formation in both marine and continental environments. They discuss the potash-forming process from the perspectives of the landform tectonic setting, brine evaporation, chemical precipitation, the separation of basin structure, provenance and the influence of the sedimentary environment and so on. On the basis of these models, by taking the potash formation process in the Lop Nur Saline Lake as an example, we aim to describe accurately and examine the coupling mechanism among the three potash-forming factors. The purpose is to deepen our understanding of the laws that govern potash formation on earth surface and in view of them shed light on the potash formation process in Chinese ancient marine basins.

2 Geological Setting

The Tarim Basin, located in the northwest of China, is one of the largest and most arid inland basins on Earth. With a diamond-like shape, the basin is currently covered by the Taklimakan Desert over almost its entire central region, and is surrounded by high mountain ranges: the Tianshan Mts. to the north, the Pamir to the west, and the Kunlun Mts. and Altyn Tagh to the south (Fig. 1a). As a superimposed basin on the craton, the Tarim basin experienced a complex evolutionary process during the Cenozoic era which is generally thought to be associated with the Indian-Eurasian collision (Burman and Molnar, 1993; Sobel and Dumitrut, 1997; Sobel, 1999; Burman, 2000; Robinson et al., 2004; Sobel et al., 2006; Dai et al., 2014). The collision resulted in the finalization of the structural shape of the basin (Xu et al., 2011) and marginal tectonic overthrusting of the surrounding mountain ranges (Burman and Molnar, 1993; Jia, 1997; Yin and Harrison, 2000; Cowgill, 2010). The resulting elevations of the surrounding mountains exceed 4000 m, whereas that of the basin only range from 800 to 1300 m (Chang et al., 2012), characterizing a marked geomorphological structure of “high mountain-deep basin” (Yuan et al., 1983; Wang et al., 2005).

The Lop Nur depression (39°40′—41°20′N, 90°00′—91°30′E) is located in the eastern Tarim Basin. It is the lowest part of the Tarim Basin and the rivers within it terminate here (Fig. 1b). Tectonically, the Lop Nur depression is situated at the junction of the Tianshan Orogenic Belt and the Altyn Mts. belonging to a sub-basin of the Tarim Basin. The present-day depression is surrounded by the EW-trending Kunuk Tag Mountain (a branch of the Tianshan Mountains) to the north (Zhang et al., 2013), the NEE-trending Beishan Block to the east, the NEE-trending Altyn Tagh Mountains to the south, and the Kuruk Desert to the west. Faults inside and around the Lop Nur depression primarily include the Kuruk Tag fault, Altyn Tagh fault, Konqi River fault, Saiisike fault, Shule River fault, southern and eastern Lop Nur faults, which exert significant control on the development of the Lop Nur depression (Liu et al., 2006a). Strata outcrops in this area are mainly composed of the sedimentary strata, volcanic strata and Quaternary sediments overlying the Archaeozoic and Mid Proterozoic metamorphic basements (Bureau of Geology and Mineral Resources of the Xinjiang Uygur Autonomous Region, 1993; Zhang, Y.L. et al., 2013).

At present, Lop Nur Lake in the Lop Nur depression is one of the world’s largest playas, occupying an area of approximately 20,000 km². Unique geological and hydrological backgrounds such as an annual rainfall of 22 mm, a peak air temperature in summer can reach 40–50°C (Yang et al., 2013), as well as a low annual precipitation of
17 mm and a high evaporation rate of 2,728 mm (Wang and Liu, 2001) make it the driest region in NW China. It has been a place of long-term mystery attracting scientists from various communities for investigations of its Quaternary environmental and climatic changes (Li, 1991; Wang et al., 2000; Lin et al., 2005; Liu et al., 2006b; Luo et al., 2009; Chang et al., 2012, 2013), formative mechanism (Guo and Zhang, 1995; Tang, 1996; Wang and Liu, 2001; Jin et al., 2005; Xia et al., 2007) and potash resources (Wang et al., 1998, 2005; Liu et al., 1999, 2003, 2005, 2008a, 2008b, 2010a, 2010b; Wang and Liu, 2001). Based on sediment types, the Lop Nur Lake can be divided into three sectors: the north sector dominated by glauberite (including the Luobei Sag and the uplift areas at both its sides), the south “Big Ear” sector and the west New Lake sector by salt crust and gypsum-bearing clayey siltstone (Fig. 2). Outcrops in the uplift areas of the north sector are composed of Upper Pleistocene strata in its interior and Pliocene strata scattered around its margins. The Holocene strata are spread over many areas including the Luobei Sag, “Big Ear” sector and “New Lake” sector. From the northern to southern Lop Nur Lake, the outcrop stratigraphic age shows a old to young change.

3 Potash Deposits of Lop Nur Lake

A superlarge-scale potash deposits in the Lop Nur depression were first found in 1995 in the Quaternary glauberite beds of the Luobei Sag (Wang et al., 1996, 1998; Wang and Liu, 2001). As a superlarge-scale and liquid potash deposit, it contains brine KCl resources of up to 250 million tons (Wang and Liu, 2001), which is nearly equivalent to the Qarqam brine potash deposit in the Qaidam Basin, Qinghai Province, Northwest China. Encouraged by the discovery of potash deposits within the Luobei Sag, potash deposits with KCl resources, exceeding seventy millions tons in total, have been found around the Luobei Sag areas in the past decade (Liu et al., 2005, 2006a, 2006b). Although most potash resources in Lop Nur Lake are contained in brines, some solid potash minerals and ore beds are also found in local near-surface areas and in salt-bearing formations (Wang and Liu, 2001).

3.1 Brine potash deposits

The brine/liquid potash deposit is the most dominant type of potash deposits in Lop Nur playa. ETM (Enhanced Thematic Mapping) of satellite images shows that brine
Potash deposits in Lop Nur Lake, covering about 1411 km², are mainly distributed in the Luobei Sag. Around the Luobei Sag several minor-scale brine potash deposits are also found in sub-sags or faulting zones. The Luobei Sag is a half-graben basin with a shallow strata bury in the south and a deep strata bury in the north. It is the deepest sag that has experienced the biggest subsidence in Lop Nur depression since the mid-late stages of the Middle Pleistocene (Liu et al., 1999, 2006a). Potash-bearing strata of the Luobei Sag are mainly in Middle to Upper Pleistocene and Holocene. Brines of the Luobei Sag are mainly stored within pores of glauconite rocks, with an average KCl content of 1.40% (wt) (Table 1) (Wang and Liu, 2001). In term of hydro-chemical classification, it belongs to the magnesium-sulphate subtype according to the categorization of Valyashko (1965). The brine formations lie from 1 m to 150 m deep, and are structurally composed by one phreatic layer and five main
Table 1 The mean values of chemical composition of brines in the Luobei Sag (After Wang and Liu, 2001)

<table>
<thead>
<tr>
<th>chemical composition</th>
<th>density (g/cm³)</th>
<th>salinity (g/L)</th>
<th>KCl (%)</th>
<th>Ca²⁺ (g/L)</th>
<th>Mg²⁺ (g/L)</th>
<th>Cl⁻ (g/L)</th>
<th>HCO₃⁻ (mg/L)</th>
<th>SO₄²⁻ (mg/L)</th>
<th>Br⁻ (mg/L)</th>
<th>F⁻ (mg/L)</th>
<th>H₂SiO₄⁻ (mg/L)</th>
<th>Li⁺ (mg/L)</th>
<th>Sr²⁺ (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1.2331</td>
<td>353.46</td>
<td>1.40</td>
<td>0.24</td>
<td>17.42</td>
<td>179.95</td>
<td>2.71</td>
<td>44.10</td>
<td>15.3</td>
<td>0.22</td>
<td>67.22</td>
<td>18.17</td>
<td>7.04</td>
</tr>
<tr>
<td>Max</td>
<td>1.2640</td>
<td>410.10</td>
<td>1.82</td>
<td>0.38</td>
<td>26.95</td>
<td>189.32</td>
<td>4.77</td>
<td>88.95</td>
<td>22.0</td>
<td>0.57</td>
<td>194.00</td>
<td>44.58</td>
<td>12.50</td>
</tr>
<tr>
<td>Min</td>
<td>1.1966</td>
<td>288.50</td>
<td>0.88</td>
<td>0.09</td>
<td>8.45</td>
<td>159.55</td>
<td>0.91</td>
<td>13.39</td>
<td>8.38</td>
<td>0.07</td>
<td>25.60</td>
<td>4.17</td>
<td>2.17</td>
</tr>
</tbody>
</table>

Annotation: Dependent on the chemical composition analysis results from more than 200 brine samples.

3.2 Solid potash resources

In contrast to the successful exploration of brine potash deposits, exploration of solid potash deposits in Lop Nur is in its infancy but also shows potential. Potassium-bearing minerals found in Lop Nur are mainly dominated by polyhalite (K₂MgCa(SO₄)₂·2H₂O) and kainite (KMgSO₄·Cl·3H₂O), with minor carnallite (KMgCl·6H₂O), sylvinite (KCl) and saltpetre (Na₂K₄Mg₂(SO₄)₆·(NO₃)₂·6H₂O). Polyhalite concentrates in the Luobei Sag in the form of thin beds (Wang and Liu, 2001; Liu et al., 2008b) and kainite occurring at the depth of 0.5 m below the surface are mainly distributed Luozhong Sag and Tienan Sag (Fig. 2) (Wang and Liu, 2001), and carnallite occurs in the Tienan Sag. Although solid potash found in Lop Nur has no real economic significance due to its lower grade and thinner ore layers, the study of its formative mechanism is of crucial theoretical importance.

4 Metallogenic Conditions of the Potash Deposits of Lop Nur Lake

4.1 Provenance

Lop Nur Lake has been a repository of the Tarim Basin catchment area since the early Pleistocene. Recharge materials for the lake are mainly supplied by the surface river systems in the Central-Western Tarim Basin (Fig. 3). The southern and northern margin of the Tarim Basin is predominantly recharged by infiltrating surface rivers, meltwater from the snow and meteoric precipitation from the Kunlun Mountains and Tianshan Mountains, respectively. The main rivers originated from Kunlun Mountains include the Hotan, Keriya, Niya and Endere Rivers. With the exception of the Hotan River that joins the Tarim River and continues to flow towards the eastern lower-lying area, the rest disappear into the southern margin of the Taklimakan Desert, recharging the alluvial-diluvial fine-sand aquifers underlying the desert. The main rivers originated from Tianshan Mountains include the Aksu, Weigan, Kuqa and Dina Rivers, which terminate at the piedmont plain with the exception of the Aksu River which flows into the Tarim River. In this case, most
ground runoff flow from the top of the alluvial fan towards its outer edge along the surface slope, resulting in these fluids eventually gathering at the basin centre from the mountain foot towards the basin interior. During this process, when surface water and groundwater arrive at the topographically lower-lying discharge areas, the salinities of water bodies continuously increase through solar evaporation. Consequently, waters with a certain salinity finally flow into Lop Nur Lake, the lowest part of the Tarim Basin. Therefore, Lop Nur depression becomes the terminal discharge area that facilitates further accumulation and differentiation of salt materials to form a superlarge-scale potash deposit.

The roles of surface rivers of the Tarim Basin in the potash formation of Lop Nur are quantitatively identified by recent studies. Bo et al. (2013) reported that the ion background value ratio (Table 2), K×10^5/(Cl^- + SO_4^{2-}) of rivers in the Tarim Basin is 14.9, which is close to that of modern seawater (K×10^5/(Cl^- + SO_4^{2-})=17.5), implying that river water in the Tarim Basin has a similar characteristic of potassium-richness to that of seawater. Based on the paleoclimate, in particular, paleotemperatures and palaeorunoff variations in the Tarim Basin, Wang et al. (2013) concluded that a total of 52.44 billion tons of potassium ions were carried from rivers in the Tarim Basin into Lop Nur Lake during the past 2Ma. These pieces of evidence suggest surface rivers are probably the most important provenance or source for the potash deposits of Lop Nur. In addition, the river water of Tarim is characterized by an extremely high SO_4/Cl (2.75) ratio that is 18 times higher than seawater (0.14) (Bo et al., 2013), enabling the high accumulation of potassium materials in Lop Nur with the deposition of large quantities of glauberite at the cost of sulfate. This therefore makes the brine-potash formation in Lop Nur Lake predate that of normal seawater during solar evaporation. Besides glauberite beds, clastic sediments of the Pliocene and lower Pleistocene have a high potassium content (Jiao et al., 2014). These potassium-bearing clastic beds probably play the role of “source bed” for the potash deposits within the overlying Late Pleistocene-Early Holocene potash deposits. The multi-stage migration of potassium ions is conducive to mineralization in the potash formation of Lop Nur Lake.

4.2 Tectonic conditions

<table>
<thead>
<tr>
<th>K (mg/L)</th>
<th>Na (mg/L)</th>
<th>Ca (mg/L)</th>
<th>Mg (mg/L)</th>
<th>Cl (mg/L)</th>
<th>SO_4 (mg/L)</th>
<th>B (mg/L)</th>
<th>Sr (mg/L)</th>
<th>Li (mg/L)</th>
<th>salinity (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.924</td>
<td>102</td>
<td>60.778</td>
<td>24.640</td>
<td>88</td>
<td>242</td>
<td>0.767</td>
<td>0.469</td>
<td>0.87</td>
<td>0.05</td>
</tr>
<tr>
<td>NaCl</td>
<td>CaCl</td>
<td>Mg/Cl</td>
<td>SO_4/Cl</td>
<td>B*100/Cl</td>
<td>Sr*100/Cl</td>
<td>Li*100/Cl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.06</td>
<td>1.16</td>
<td>0.69</td>
<td>0.28</td>
<td>2.75</td>
<td>0.87</td>
<td>0.76</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.2.1 Formation and development of the Lop Nur depression

The geological and environmental evolution of the Lop Nur depression has been explained by different researchers and is generally believed to be associated with the India-Asia collision and the Tethys system which resulted in the special geological and structural background of the northeastern Tarim Basin during the Cenozoic (Guo and Zhang, 1995; Wang and Liu, 2001). The occurrence of marine fossils in the Kuqa depression indicates that the large part of the Tarim Basin, had more likely been occupied by the Paratethys Sea during the early Cenozoic (Hao et al., 1982; Wang and Liu, 2001; Guo et al., 2002; Zhang, H. et al., 2013), the Paratethys finally retreating westward from the basin during the late Eocene to early Oligocene (Bosboom et al., 2011, 2014). Up to the late Neogene, the Tarim Basin had existed as an integrated lake (Wang and Liu, 2001; Wang et al., 2006), with the main depositional center in its western part, although large-scale salt deposits occurring in the Kuqa depression (Liu et al., 2013a) indicate a migration of the depositional center of the integrated Tarim Lake. During this interval, the Lop Nur depression was still not formed and the Lop Nur area as a topographic highland experienced wide erosions as the Tarim Basin was still inclined from east to west (Mu et al., 2001). This situation continued until Pliocene or the early Pleistocene, when the southwestern and southeastern parts of the Tarim Basin were uplifted as a result of the growth of the Tibetan Plateau and its neighbouring areas (Tang, 1996; Mu et al., 2001; Dong et al., 2012). In western Tarim, convergence between the Pamir and Tianshan Mts. since the Late Miocene and Pliocene led the Pamir to move northward about 600 km with its foreland part being shortened by about 300 km (Burtman and Molnar, 1993; Burtman, 2000). The northward movement of the Pamir might have led to the connection of the Pamir with the Tianshan and closure of the Alay Valley during the Early Pleistocene (ca.2.1 Ma, Zhang, Z.G. et al., 2013). A wide syntectonic development of growth strata in the Boguzihe section (Heermance et al., 2007; Zhang, Z.G. et al., 2013) and other places on both sides of the Tianshan (Sun and Liu, 2006; Charreaux et al., 2008; Huang et al., 2010; Li et al., 2010), accompanied by great increases in coarse sediments and the sedimentation rate, strongly suggests a wide and rapid uplift of the Tianshan during the Pliocene to
Quaternary. In the southern Tarim Basin, desertification recorded by paleo-sand dunes and loesses in alluvial conglomerates in the early Pliocene (Zheng et al., 2000; Sun and Liu, 2006; Sun et al., 2009) is probably the result of the impact of a rain shadow caused by the rapid rising of the Tibetan Plateau and Kunlun Mountains. These lines of evidence indicate a wide and rapid uplift of the western and southern Tarim Basin since the Pliocene that alters the east-west inclination of the Tarim Basin. Together with the change in the inclination, the NNE-SSW principal compression stress caused by the Indian-Eurasian collision has exerted significant control over the partitioning of the sub-basin structural units of the Tarim Basin (Guo and Zhang, 1995; Wang and Liu, 2001), forming the Lop Nur depression as the lowest point of the Tarim Basin (Liu et al., 1999, 2008a; Wang and Liu, 2001; Xia et al., 2007). Previous studies proposed that the Lop Nur depression formed during the end of the Early Pleistocene to the earliest stage of the Mid Pleistocene (Mu et al., 2001) and occurred as the centre of water convergence much later (Xia et al., 2007). However, the discovery of the thin-layer gypsum and magnesites occurring within the Pliocene strata of the north and northeastern parts of Lop Nur, indicates that at this period (i.e. closed and relatively long-term water convergence) Lop Nur had received the discharges from rivers of the Tarim Basin and had experienced short-term saline lake conditions. This is consistent with the wide and rapid uplift of the western and southern Tarim Basin since the Pliocene. The formation and evolution of the Lop Nur Lake is summarized in Fig. 4 based on the compilation of data from drill cores, outcrop sections, paleogeography, regional tectonism and sedimentary records and so on. It shows that the Lop Nur depression formally emerged to serve as an actual repository of the Tarim Basin during the late Pliocene (Fig. 4II), when Lop Nur had developed into topographically water-logged sag from the Miocene slip landform (Fig. 4I). During the Early Pleistocene, substantial subsidence of Lop Nur Lake took place and the previous freshwater lake environments in this area gradually developed into brackish water, where thin-layered gypsum was deposited (Fig. 4III). With solar evaporation continuing, brackish lake environments in Lop Nur Lake changed into saline lake environments, from around the Mid Pleistocene. Sediments of Lop Nur Lake during this interval are characterized by the predominant glauberite with gypsum which decreased in relative terms (Fig. 4IV). At the end of the Pleistocene, the differential elevation and subsidence of the Lop Nur “depression floor” caused by the NNE-SSW principal compression stresses, resulted in the formation of a series of graben-faults, sub-depressions like the Luobei Sag, partitioning the previously integrated Lop Nur depression (Fig. 4V). The northern part of the Lop Nur depression as a whole is an uplifted area with a relatively higher position. However, the Luobei Sag within the depression has the deepest subsidence and has a basement inclined to the north. This makes the Luobei Sag a fairly closed unit, providing a good tectonic accommodation space for potash deposits.

4.2.2 Formation and development of the Luobei Sag for potash formation

The Lop Nur depression has mainly been controlled by S-N compression stress since the Cenozoic (Xie et al., 1989; Bai, 1992; Fan, 1993; Wang and Liu, 2001; Zhang et al., 2001; Chen et al., 2001; Liu et al., 2006a, 2007). Numerical and physical simulations indicate that in addition to the S-N compression stress, the NE principal compressive stress since the Late Miocene has also exerted control over the Oligocene-Miocene period. Both sets of compression stresses made the Lop Nur escape westwards under an E-W stretching tension in its interior (Shi et al., 2009).

Under the S-N compression stress, graben-type fault systems and a series of sub-depressions were formed in Lop Nur depression (Fig. 5), most areas of the northern Lop Nur experienced uplift. On the other hand, the graben-type faulting parallel to the principal compressive stress (Liu et al., 2006a) and the conjugate faulting left behind a “lineament grid” tectonic pattern in Lop Nur (Wang and Liu, 2001). In the northern uplifted parts, faulting and subsidence resulted in the formation of the Luobei Sag, of which the basement inclined to the north (Wang and Liu, 2001) is in opposition to the overall inclination of the northern uplifted area. In the southern parts, the previous lake was progressively enlarged and developed into the latter Big Ear Lake, through continuous subsidence. This builds a “threshold” between the newly-born Luobei Sag in the north and the Big Ear Lake in the south (Wang and Liu, 2001; Liu et al., 2010a), creating a “closed potash-gathering tectonic space”. However, the key to the above scenario is that the sedimentation rate should be higher in the Luobei Sag than in the northern Big Ear Lake area (Fig. 5). This assumption was recently vindicated by the evidence that the sedimentation rate since the end of the Early Pleistocene is 0.08 mm/a (paleomagnetic polarity dating) in the K1 core in the Big Ear Lake, while the sedimentation rate since the Mid Pleistocene is 0.42 mm/a (uranium series dating) in the ZK0800 core in the Luobei Sag (Wang and Liu, 2001).

4.3 Climatic conditions

The Lop Nur depression in the northern Tarim Basin is the most arid region of Central Asia located at the
Fig. 4. Sketch map of the generation and development of Lop Nur Lake.
boundary between the East Asian summer monsoon area and the westerly winds of the Northern Hemisphere (Lehmkuhl and Haselein, 2000; Yang and Williams, 2003). In the past two decades, significant progress has been made in the climatic reconstruction of Lop Nur during the Cenozoic, especially the Late Cenozoic, which has further increased our understanding of the environmental changes in this region and the Tarim Basin or even Central Asia during this interval. Previous studies suggested that the arid environment of the Tarim Basin began at the end of the Tertiary and was fully formed in the Quaternary (Xia et al., 1987). However, recent geochemical records of lacustrine-fan delta sediments from the western Tarim Basin indicate that an arid climate had prevailed within the basin since at least ca. 5.7 Ma and had gradually increased in severity until ca. 3.7 Ma (Zhang, Z.G. et al., 2013). Consistent with the result from the western Tarim Basin, magnetic susceptibility together with other climatic proxies from core LS2 of Taimeta Lake of Lop Nur in the eastern Tarim Basin (Chang et al., 2012, 2013) also suggest an enhancement of aridity in the basin since the late Miocene (ca. 5.6–5.1 Ma). On the basis of pollen assemblage, the climate of Lop Nur was mainly characterized by semi-arid climate conditions during the middle of the Early Pleistocene to the end of the Late Pleistocene (~30 ka), only interrupted by arid climate conditions during 27–40 ka (Wang et al., 2000; Wang and Liu, 2001). Recent high-resolution pollen sequences from Lop Nur (Yang et al., 2013) divides the environmental changes during the late Pleistocene to the early Holocene into four stages: a cold-wet climate condition for 31.98–19.26 ka; a warm-arid climate condition for 19.26–13.67 ka; a cold-wet climate for 13.67–12.73 ka and a warm-arid climate for 12.73–9.14 ka. Paleoclimatic parameters obtained by collating the palynological data and by applying the method of Coexistence Analysis (Hao et al., 2012) suggest that temperatures in Lop Nur increased from the late Miocene (10.2°C) to the Pliocene (13.4°C), decreased from the Pliocene to the Pleistocene (4.7°C), and were more stable from the beginning of Holocene (12.1°C) until now (11.5°C); the precipitation of Lop Nur was stable (about 900 mm) from the Late Miocene to Early Pleistocene, then decreased markedly (about 300 mm) in the Mid and Late Pleistocene, and reached its lowest value (17.4 mm) in the Holocene. Although an accurate time constraint on the emergence of the arid climate and the detailed phase variation of climate changes of the Lop Nur or the Tarim Basin during the Cenozoic era is still uncertain, an arid climate has occurred at least as early as the late Miocene in the Tarim Basin (Guo et al., 2002; Dong et al., 2012). The climatic conditions of Lop Nur increasingly got drier on a long-term time scale from then to now that can be inferred based on the preceding lines of evidence.

Besides the climatic proxies mentioned above, in evaporite basins salt mineral assemblages can also be used as good indicators for climatic changes. As shown in Fig. 6, gypsum and glauberite dominate almost the entire salt-
bearing sequence in the core ZK08000 suggesting the existence of a prevailing arid and warm climate since the Mid-Pleistocene (Liu et al., 2007). Our statistics on salt minerals in modern saline lakes indicate that the evaporite-mineral species is linearly related to evaporation rate (Fig. 7). The local evaporation rates corresponding to carbonatite, gypsum, glauberite, halite, kainite, sylvite and carnallite are 900, 1030, 1650, 2000, 2728, 3297.9 and 3518.5 mm/a, respectively. This suggests that the evaporation rate of lake water experiences a modest progressive increase from carbonate stage to gypsum stage, a rapid increase during the stage of glauberite and halite deposition, a more rapid increase during the stage of kainite, sylvite, and carnallite deposition stage, respectively. Since evaporation rate is always thought to be associated with the extent of arid climate, therefore, gypsum can be defined as a proxy indicating semiarid climate, halite as arid climate, and sylvite or carnallite as an extremely arid climate. Therefore, the Holocene thin-layered kainite (Wang and Liu, 2001), sylvite and carnallite beds (Liu et al., 2010b; 2011; Jiao et al., 2014),

and the late Pleistocene huge glauberite deposits in Lop Nur suggest that (1) climate conditions probably became more arid from the Late Pleistocene to the Holocene and; (2) an extremely arid climate prevailed in Lop Nur during Holocene. This climate condition results in a quick and intensive evaporation of brines in Lop Nur Lake, and potash deposits formed during a very short period which can be referred to as “flash evaporation”.

5 What is the Potassium Enrichment Mechanism When the Conditions of Provenance, Climate and Tectonics are all Met?

5.1 Time-longitudinal preparation of potassium pre-enrichment

The Hongtubao Section outcrop occurs at the northwest margin of the Lutobei Sag (Fig. 2). Chemical analysis of 30 samples (sandstone and gypsum) from the section indicates that the main components of the soluble salts includes Na, Ca, Mg, K, CI and SO_4^{2-} and trace elements commonly existing in a saline lake include B, Sr and Li (Table 3). K⁺ content with a maximum, minimum, and average value of 0.92%, 0.10% and 0.39%, respectively, exhibit a three peak value of 0.80%, 0.80% and 0.90%. Ca^{2+} is positively correlated with SO_4^{2-} and develops three peaks implying three thin gypsum layers. Chemical component data indicates that the K-rich river supplies in the Tarim Basin together with the arid climate conditions had led potassium(K) (usually in the form of adsorption by clay) to be enriched within the Pliocene fine-grain sediments and early-stage salt minerals. These early relatively K-rich salt sequences with an average KCl value of 0.39% play a role as an initial “ore-source bed” for
Table 3 Major components of soluble salts from the Pliocene strata in the Hongtubao outcrop

<table>
<thead>
<tr>
<th>Ion contents</th>
<th>Na⁺ (%)</th>
<th>K⁺ (%)</th>
<th>Ca²⁺ (%)</th>
<th>Mg²⁺ (%)</th>
<th>Cl⁻ (%)</th>
<th>SO₄²⁻ (%)</th>
<th>Br⁻ (%)</th>
<th>Sr²⁺ (%)</th>
<th>Li⁺ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.22</td>
<td>0.39</td>
<td>2.10</td>
<td>0.85</td>
<td>4.56</td>
<td>7.16</td>
<td>0.007</td>
<td>0.007</td>
<td>0.0014</td>
</tr>
<tr>
<td>Max</td>
<td>9.49</td>
<td>0.92</td>
<td>19.30</td>
<td>5.43</td>
<td>16.56</td>
<td>45.20</td>
<td>0.014</td>
<td>0.039</td>
<td>0.0022</td>
</tr>
<tr>
<td>Min</td>
<td>0.58</td>
<td>0.10</td>
<td>0.04</td>
<td>0.14</td>
<td>1.54</td>
<td>1.64</td>
<td>0.002</td>
<td>0.004</td>
<td>0.0005</td>
</tr>
</tbody>
</table>


Table 4 The major components in the middle-Lower Pleistocene elastic sedimentary rocks of the Luobei depression (LDK01 Drillhole)

<table>
<thead>
<tr>
<th>Ion contents</th>
<th>Na⁺ (%)</th>
<th>K⁺ (%)</th>
<th>Ca²⁺ (%)</th>
<th>Mg²⁺ (%)</th>
<th>Cl⁻ (%)</th>
<th>SO₄²⁻ (%)</th>
<th>Br⁻ (%)</th>
<th>Sr²⁺ (%)</th>
<th>Li⁺ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.4893</td>
<td>0.3979</td>
<td>7.3278</td>
<td>2.5342</td>
<td>3.5107</td>
<td>12.6377</td>
<td>0.0795</td>
<td>0.0112</td>
<td>0.0026</td>
</tr>
<tr>
<td>Max</td>
<td>10.8596</td>
<td>1.4999</td>
<td>26.0829</td>
<td>7.3699</td>
<td>12.6179</td>
<td>66.5383</td>
<td>0.1581</td>
<td>1.1395</td>
<td>0.0084</td>
</tr>
<tr>
<td>Min</td>
<td>0.0706</td>
<td>0.0359</td>
<td>0.1440</td>
<td>0.2744</td>
<td>0.4487</td>
<td>0.1023</td>
<td>0.0213</td>
<td>0.0003</td>
<td>0.0003</td>
</tr>
</tbody>
</table>


Table 5 Composition of the brine between the gypsum-bearing strata and inclusions in gypsum

<table>
<thead>
<tr>
<th>Inclusions in gypsum</th>
<th>K⁺ (g/L)</th>
<th>Mg²⁺ (g/L)</th>
<th>Br⁻ (mg/L)</th>
<th>B⁻ (mg/L)</th>
<th>Li⁺ (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brine</td>
<td>3.11</td>
<td>4.17</td>
<td>0.97</td>
<td>35.61</td>
<td>13.59</td>
</tr>
</tbody>
</table>

Gypsum samples obtained from Luobei depression (LDK01 Drillhole); Brine samples obtained from the “Big Ear” lake; Testing units: The supergene geochemistry lab of the Institute of Mineral Resources, Chinese Academy of Geological Sciences (After Liu et al., 2013b)

5.2 Horizontal preparation of potash enrichment during the lake deposition contraction

In terms of the NE-SW trending structural section, the Lop Nur depression is composed of several sags (Fig. 5), among which the Luobei Sag is the key and most important one for potash deposition. According to the sedimentary facies distribution, Lop Nur depression is a complex sedimentary basin system characterized by the multi-stage migration of sedimentary facies during lake shrinkage (Fig. 8 and 9). On the basis of remote sensing interpretation and field investigation, combined with core correlation results, the sedimentary system of Lop Nur Lake in temporal and spatial evolution can be divided into five stages. Each stage corresponds to a type of “basin-deposition” system with specific sediments, that is, the clastic-facies basin, gypsum-facies basin, glauberite-facies basin, halite-facies basin and potash-facies basin (solid potash is not discussed here as it is not industrially significant), respectively. The area of each type of “basin” is inferred using the ArcMap software based on related geological parameters and is listed in Table 6.

As brine concentration increases, salt mineral contents and their distribution area display a logarithmic decrease (Fig. 10). The clastic-facies basin occupies almost the entire Lop Nur depression with an area of 20,521 km², while the gypsum-facies basin (with an area of 9,137 km²) is only about 45% of the clastic basin, the glauberite basin (4,959 km²) is about 53% of the gypsum basin, and the halite basin (1,499 km²) is about 30% of the size of the glauberite basin. The halite overlying the glauberite layer is concentrated in the Luobei Sag, with a total thickness of 2–3 m. The solid potash sediments are mainly distributed in Luozhong in the north of the Big Ear Lake (Fig. 2), only covering an area of 43.52 km². With a thin ore bed (~0.5

Table 6 The areas of sedimentary facies “basins” in Lop Nur depression

<table>
<thead>
<tr>
<th>Number</th>
<th>Classification of facies basin</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>clastic basin</td>
<td>20521.500</td>
</tr>
<tr>
<td>2</td>
<td>gypsum basin</td>
<td>9117.0400</td>
</tr>
<tr>
<td>3</td>
<td>glauberite basin</td>
<td>4959.8700</td>
</tr>
<tr>
<td>4</td>
<td>halite basin</td>
<td>1499.6400</td>
</tr>
</tbody>
</table>
Lop Nur Lake experienced a continuously northward contraction until the Luobei Sag. Contraction of the lake is probably more intensive prior to the glauberite deposition, and slightly released thereafter. When it evolved to the saline lake stage, the deposition was concentrated in the Luobei Sag, which has been evolved into the deepest subsidence area. With regard to horizontal distribution, the gypsum basin plays a role as a preparatory basin for the glauberite basin which in turn plays the role as a preparatory basin for the later halite basin. The above process combined with arid climate conditions and a decrease in source recharges make these preparatory basins gradually contract, the salt components becoming continuously concentrated, providing the material foundation for the potash deposit.

In terms of spatial and temporal distribution, potassium-bearing sediments occupy an area of approximately 20,000 km² of Lop Nur and occur through the Pleistocene to
Holocene strata with different lithotypes. In this case, static pressure of the overlying layers caused by sediment superposition will lead pore or intercrystalline brine within the underlying layers to migrate upwards by way of transfluence, providing “transfluence recharge” for potash deposition (Liu et al., 2013b). In addition, soluble potassium materials leached from the potassium-bearing formations discussed above (“ore-source bed”) through the chemical weathering and the deep circulation of meteoric precipitation can also provide material supplies for potash deposition in the surface saline lake (Liu et al., 2003).

5.3 Potash formation mechanism—the linkage of provenance-tectonics-climate

As previously mentioned, potash formation in Lop Nur experiences an earlier multi-stage accumulation and preparation of potassium materials and a later quick ore-formation due to “flash evaporation”. This reveals not only the special metallogeny of the potash deposits of Lop Nur but also a linked process of tectonic, provenance, and climatic factors. We divide the process into four stages as follows:

Stage I: In the Pliocene, Lop Nur depression effectively became the repository of the Tarim Basin catchment area since it had developed into the topographic “pan” relative to the Miocene “slope” landform (Fig. 4 I, II). This can be shown by the gypsum and magnesite that occurred within the Pliocene strata which suggests that a perennial lake had already emerged and was receiving the river recharges of the Tarim Basin. Under the joint action of potassium-rich river supplies and semiarid climate conditions, especially through the process of clay absorption, potassium began to be enriched within the Pliocene fine-grain sediments and early-stage salt minerals. This gave rise to the “initial potassium ore-source bed”, of which KCl in sedimentary rocks has an average value of 0.40%.

Stage II: In the Early Pleistocene, the “pan” subsided significantly and continuously accepted lacustrine deposits (Fig. 4 III). With massive gypsum deposits and further evaporating, brines of the lake evolved into a kind of “potassium-bearing brine” with a KCl content up to 0.30%, and subsequently migrated into and were stored in the pores of clastic rocks. In the meantime, clastic rock continued to “capture” soluble potassium ions and finally became the principal “ore-source bed”. With its gigantic volume, the clastic rock can therefore accommodate a huge deal of potassium and provide more material supplies for subsequent potash formation.

Stage III: In the Middle Pleistocene, when glauberite started to be deposited (Fig. 4 IV), potassium ions were further enriched in the brine, and more “potassium-bearing brine” was formed among the glauberite crystals, evidenced by the fact that most of the fluid inclusions in glauberite contain 5–10 g/L potassium. According to numerical simulation of brine evaporation (Liu et al., 2013b), the analyzed potassium ion content in the brine when the glauberite deposited was 0.65%–1%, which is close to the potassium content of the fluid inclusions in glauberite.

Stage IV: In the Late Pleistocene (Fig. 4 V), the extensive deposition of glauberite occurred and caused the potassium level increasing further in brine. In addition, Late Pleistocene saw a strong differential rise and fall of the basement of the Lop Nur “pan”, causing the northern part of Lop Nur to become uplifted extensively and gave shape to the “preparing-evaporating” lake chain system along the connecting line of Taitema Lake, Big Ear Lake and Luobei Sag (Fig. 5). Meanwhile, tectonic activities caused the Luobei Sag to receive deposits at a greater rate than the Big Ear Lake area in the south, and its basement subsidence was also the deepest. This also enabled the evaporated and concentrated brine in the preparatory sags to sink into the Luobei Sag. The gathered brine was then intensely concentrated by evaporation, losing a lot of water through “pumping” to the atmosphere. Therefore, salinity and potassium ion concentration in the brine further increased, eventually causing the formation of the brine potash deposits.

As discussed above, potash formation is dependent on the joint action of provenance, tectonics, and climate, which is in agreement with the view on marine evaporite forming (Warren, 2010). The joint action between exogenetic and endogenetic forces of the Earth is also essential. The exogenetic force (solar energy) caused the surface weathering of materials and moisture evaporation, while the endogenetic forces contributed to the formation of a potash-gathering tectonic space which here is also called a “lake-chain” tectonic space. In the lake-chain system, the “subbasin” being far away from the recharge sources is more conducive to potash formation, and its deposition rate being greater than that of the preparatory subbasins, which is one of the key decisive factors for the mineralisation of potash. On the other hand, climatic changes, especially the occurrence of extremely arid climates, which could be either regional or global, could have made vital contributions to potash formation. The deposition of potash, especially the deposition of chloride-type potash, requires an extremely arid climate (i.e. the evaporation rate must be 3200 mm/a or greater). In a generally arid climate zone, such an extremely arid climate may have been both an outbreak and also may only have lasted for a relatively short period of time. Thus, the possibility of potash deposition was far more remote than that of halite deposition.
Based on the discussion above, potash generation in basin system should be summarized as follows (Fig. 11).

(1) Material preparation. The drainage area of the basin was continuously recharged by abundant potassium-bearing waters, including the continuously supplied relatively “potassium-rich” river water and the “ore-source bed” (older depositional formations), which could have become recharge resources for potash and other ore-forming materials due to weathering processes. Hence, recharged by an abundant provenance, the ore-forming materials are able to accumulate continuously in the basin;

(2) Tectonic space preparation. The basin should have evolved over three stages: a formative stage, a developing stage, and a shrinking-separating stage. This resulted in a potash-forming system which comprised both the preparatory sub-basin and potassium-forming sub-basin, in which the deposit rate of the latter was greater than that of the former. Then the brine of the preparatory saline lake could gather in the subsag with the deepest subsidence;

(3) Intense concentration and “pumping”. The brine flowing from the preparatory sub-basin into the potassium-forming sub-basin demands an even more arid climatic environment to continue to evaporate and enable its H2O vapour to be “pumped off” into the atmosphere. Therefore, an extremely arid climate (an evaporation rate of 3200 mm/a or higher) should be readily secure. When this climate appears in the basin, the brine in the potash-forming sub-basin will be intensely concentrated by evaporation, and potash deposits will eventually be formed (Fig. 11).

Therefore, the linkage among provenance, tectonics, and climate for potash mineralisation was not simply the superposition of these factors. Instead, the three factors have exhibited a structural coupling mechanism, i.e. the linking of the “extreme components” of these factors.

6 Conclusions

Following the study of the potash formation process in the Quaternary Lop Nur saline lake, it is concluded that potash mineralisation is dependent on an abundant provenance/source, a suitable gathering space, and intense evaporation.

(1) The recharged water from the drainage area of the Tarim Basin for the potassium provenance of Lop Nur had an equivalent K/(Cl+SO4) ratio to that of seawater. This is the first factor that provided a material basis for potash formation. However, recharge of ore-forming materials did not simply mean that surface water flowed into the lake. Instead, the supplied materials were enriched progressively over several stages, even to form “ore-source beds”. This type of recharge may well have been extremely important for the mineralisation of potash.

(2) Macroscopically, the collision-extrusion between the Indian and Asian plates, especially in the west, caused the basement of the Tarim Basin to revert in landform, that is, it changed from “higher in the east” to “higher in the west”. This gave shape to the closed Lop Nur depression, causing the water bodies of the Tarim Basin to drain into it; thus, enormous quantities of potassium were carried into Lop Nur Lake. Locally, the nearly S-N compressive stress on the Lop Nur area caused the depression to be further separated into some sub-depressions that together made up a “lake-chain” system, with the Luobei Sag being the most closed sag and that with the deepest subsidence.

![Fig. 11. Sketch map of the evolution and linked factors for potash formation among “provenance, tectonics and climate” in an evaporation basin system. Vpb—Deposition rate of the preparatory basins, Vsb—Deposition rate of potassium—forming sub—basin.](image-url)
This provided a tectonic space for the gathering of potash. (3) As a precondition that potassium continued to recharge the Lop Nur Lake, extremely arid climatic conditions are essentially needed. After the brine had undergone intense evaporation under extremely arid climate in late Pleistocene and Holocene, potash deposits were formed on a large scale in Luobei Sag. (4) The three factors (provenance, tectonics, and climate) have developed collaboratively since the very beginning of saline lake evolution. More significantly, they have exhibited a structural coupling mechanism (i.e. the linking of their “extreme components”).

Acknowledgements

This research is funded by the National Basic Research Program of China (No.2011CB403007) and the State Key Program of National Natural Science of China (No. 40830420). The participants also include Prof. Chen Yongzhi, Associate Prof. Ma Lichun, PhD student Wang Wenxiang and MA students Wang Xin and Zhao Huitong etc., and Fan Li, Wang Fenglian and Han Erbin drew the charts. Constructive comments on the manuscript by referees are gratefully acknowledged.

Manuscript received Oct. 10, 2015 accepted Nov. 2, 2015 edited by Liu Lian

References


Liu Yongjiang, Neubauer, F., Ge Xiaohong, Genser, J., Yuan


Yang Dong, Peng Zicheng, Luo Chao, Liu Yi, Zhang Zhaozong,


**About the first author**
LIU Chenglin: Male; born in 1963 in Funing city, Yunnan Province; Researcher; Doctoral supervisor; work in the Institute of Mineral Resources, Chinese Academy of Geological Sciences; His research interests are mainly in saline lake sedimentary and potash deposits.