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Distribution, characteristics, metallogenic processes and prospecting potential of terrestrial brine-type lithium deposits in the world and lithium demand situation

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ABSTRACT

In response to the rise of the energy storage industries such as new energy vehicles and the wide application of lithium in various fields worldwide, the global demand for lithium resources has been in explosive growth. In order to further comprehensively understand the global supply and demand pattern, development and utilization status, genesis of ore deposits and other characteristics of lithium resources, based on the achievements of many researchers at home and abroad, this paper systematically summarized the lithium supply and demand situation, resource endowment, deposit classification and distribution, typical geological characteristics, metallogenic factors and metallogenic regularity of terrestrial brine-type lithium deposits which are the main types of development and utilization all over the world. The review shows that brine-type lithium resource and (or) reserves in the plateau salt lakes are huge and play an important role. In addition, the mineralization potential of the underground brine-type lithium deposit is broad worldwide. The potential resources of underground brines are enormous, and the geothermal spring water type is also worthy of attention. Brine lithium deposits are mainly controlled by the subduction and collision of regional plate tectonics, arid climate and provenance conditions. Strengthening of the scientific research on underground brines in the future is expected to provide another significant support for the global demand for lithium resources.

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1. Introduction

1.1. Uses of lithium

Lithium possesses numerous outstanding physical and chemical properties. It is widely used in the aerospace industry because it is the lightest metal on the earth and is applied to nuclear fusion reactors due to its low melting point and high boiling point. Additionally, it is being implemented in new energy lithium batteries and other energy storage fields due to its low electronegativity. In addition, lithium has a wide range of applications in traditional fields such as glass, lubricants, ceramics, and medical care, as well as in emerging fields such as energy storage, adiabatic materials, polymer materials, and the photovoltaics industry (Wang GS, 2001; Shen J and Dai BL, 2009; Yaksic AY and Tilton JE, 2009; Gruber PW et al., 2011; U.S. Geological Survey (USGS), 2019; Ejeian M et al., 2021). In recent years, lithium has been classified as a key mineral resource by many countries, including China, the United States, the European Union, and Japan and so on (Wang GS, 2001; USGS, 2019, 2023; Liu CL et al., 2021).

1.2. Lithium demand situation

With the growth of the new energy automobile industry from 2012 to 2022, the price of lithium carbonate has risen drastically, and lithium mines have become the target of competition among mining enterprises. Meanwhile, strong demand from the downstream industry has naturally led to the broad exploration and large-scale development of upstream primary products. Due to the strong demand for lithium and the rapid price growth in 2022, the global lithium industry is

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expected to expand, leading lithium producers to enhance their production capacity. This trend is expected to continue in the coming years (Fig. 1; Smith GI et al., 1983; Schulz KJ et al., 2017; Sun X et al., 2022; USGS, 2023).

1.3. Exploration and exploitation status of lithium deposits

Most of lithium deposits are distributed in Bolivia, Argentina, Chile, the United States, Australia, China, Canada, and other countries, with a resource of about 98 million metric tons (Mt). The reserves are primarily concentrated in Chile, Australia, Argentina, China, and so on, with total reserves of approximately 26 Mt (USGS, 2023). Australia, Chile, China, and Argentina supply most of the world's lithium ore. In addition, some small-scale producers, including Portugal, Canada, Brazil, Zimbabwe, and Canada, also supply a portion of their lithium products (Fig. 2).

According to the occurrence and resource utilization mode of lithium, lithium deposits are classified into hard rock-, brine- and unconventional-type (Kesler SE et al., 2012; Mohr SH et al., 2012; Bradley D et al., 2013; Munk LA et al., 2016; Benson TR et al., 2017; Kavanagh L et al., 2018; Coffey DM et al., 2021). The hard rock types are further subdivided into granite-pegmatite and alkaline feldspar granite subtypes (Fei GC et al., 2020; Zhao YJ et al., 2021). Brine types are subdivided into salt-lake brine in plateau salt lakes (Zheng XY et al., 2002; Hofstra AH et al., 2013), underground brine (oilfield brine) (Vine JD, 1976; Bottomley DJ et al., 2003; Birkle P et al., 2009), and geothermal brine subtypes. Unconventional types are classified into clay type, lithium zeolite type, etc (Glanzman RK et al., 1978). At present, the primary types of mining and utilization are brine type in plateau salt lakes and hard rock type. The total amount of brine-type lithium resources in salt lakes is greater than that of hard rock type (Kesler SE et al., 2012; Tomascak PB et al., 2016). The development and utilization costs of brine Li deposits are 2–3 times lower than that of hard rock type, their yields accounting for 64% of the current development and utilization (Kesler SE et al., 2012; Munk LA et al., 2016; Tomascak PB et al., 2016; USGS, 2023). The percentage of

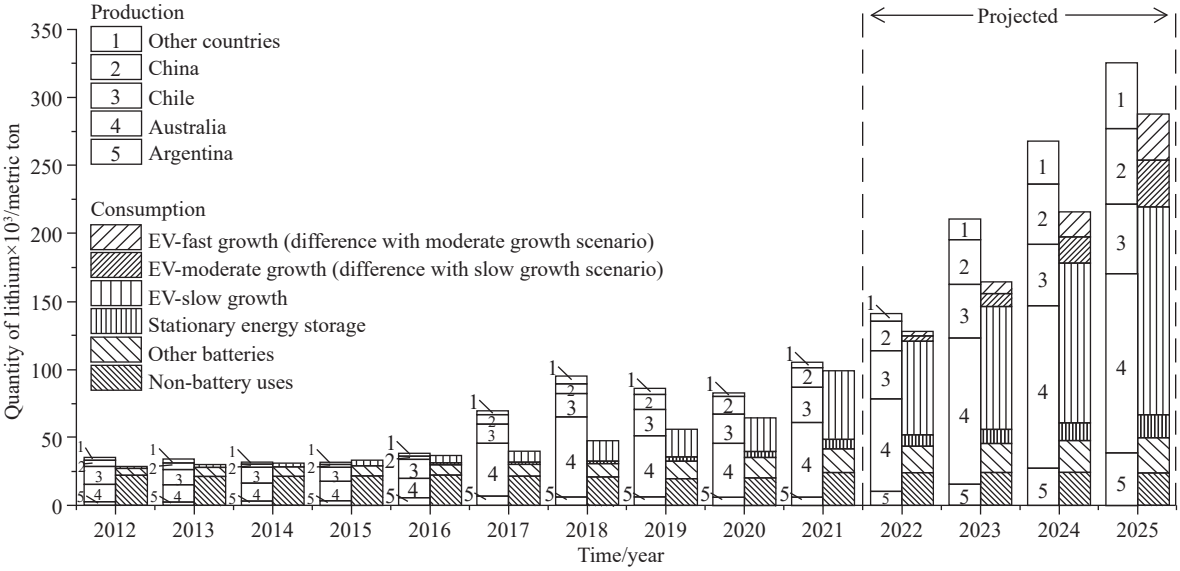

Fig. 1. Past and projected production and consumption of global lithium mines (after Sun X et al., 2022; USGS, 2022).

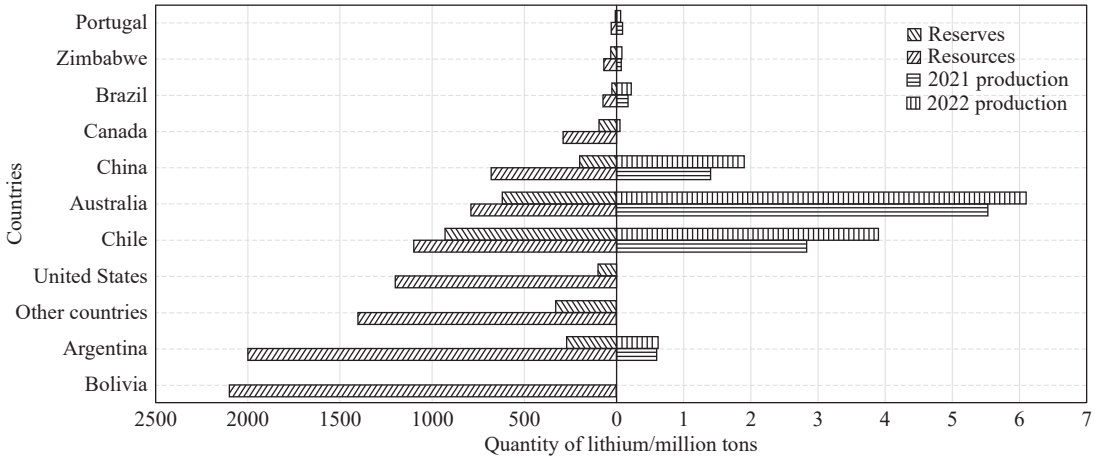

Fig. 2. Main lithium ore resources and reserves distribution and the main lithium mineral products producing countries worldwide (after USGS, 2022).

various types of lithium deposits for development and utilization is as follows: Brine lithium deposits in plateau salt lakes account for 58%, pegmatitic-type for 26%, clay-type for 7%, underground brine (oilfield brine) for 3%, geothermal brines for 3%, and lithium zeolites for 3% (USGS, 2023). Pegmatite-type lithium deposits are primarily found in Australia, Zimbabwe, China, and the United States. Clay-type lithium resources are primarily located in Mexico, the United States, Peru, and Serbia. Brine-type lithium deposits are primarily found in Argentina, Bolivia, Chile, China, and the United States. (Kesler SE et al., 2012; Liu LJ et al., 2017; USGS, 2023) (Fig. 3). In this study, the authors have summarized and analyzed the distribution, geological characteristics, metallogenic mechanisms of different types of terrestrial brine deposits worldwide. The paper aim is expected to be conductive to the exploration of lithium deposits and the discovery of more lithium resources for geologits in the near future.

2. Distribution of brine-type lithium deposits

Brine-type lithium deposits in salt lakes are primarily located on the three major plateaus in the world: The Andean Plateau in South America, the Western Plateau in North America, and the Qinghai-Tibet Plateau in China. The underground brine-type deposits (oilfield brine) have been found in South China in recent years, such as in the Jianghan (Li RQ et al., 2013; Shen LJ et al., 2014; Liu CL et al., 2016; Wang CL et al., 2018, 2021a) and Jitai Basins (Wang CL et al., 2020). In other parts of the world, the underground Li-rich brines are discovered boradly, such as the Siberia platform (Alexeev SV et al., 2020).

2.1. Andean Plateau of South America

There are hundreds of salt lakes distributed in closed basins in the Andean Plateau of South America. Brines in salt lakes are endowed with significant amounts of lithium (Li), potassium (K), magnesium (Mg), boron (B), bromine (Br), rubidium (Rb), cesium (Cs), and other elements, marking a valuable source of important minerals globally. Among those salt lakes, the most famous salt lakes are Uyuni in Bolivia, Atacama in Chile, and Hombre Muerto in Argentina. The region encompassed by the three salt lakes is known as the "Lithium Triangle" due to its high-grade and huge lithium resources (Fig. 4; Supplementary Table 1). The area, elevation, lithium concentration, and resource reserves of brines in salt lakes on the plateau are shown in Supplementary Table 2. The larger salt lakes include Uyuni (10580 km^2), Atacama (3000 km^2), Coipasa (2500 km^2), Arizaro (1708 km^2), Antofalla-Botijuelas (655 km^2), and so on. The concentration of lithium in brine ranges from 57 mg/L to 1490 mg/L. Among them, the lakes with relatively high lithium concentrations include Olaroz (260–1490 mg/L), Atacama (1400 mg/L), Pozuelos (96–940 mg/L), Cauchari (860 mg/L), Uyuni (316–602 mg/L), Hombre Muerto (521 mg/L), Pastos Grandes (483 mg/L), and others. The salt lake with the largest lithium resource reserves is Uyuni (10.2 Mt), followed by Atacama (6.3 Mt), Olaroz (1.5 Mt), Rincon (1.1 Mt), Cauchari (1.06 Mt), Diablillos (0.9 Mt), and Hombre Muerto (0.8 Mt). The Mg/Li ratio is a crucial index for measuring of the extraction cost of brine. A lower ratio indicates a more efficient extraction process. The Mg/Li ratios in the brines of the South American plateau are generally very low, ranging from 0.01 to 1.24, with an average value of 0.45. These ratios indicate that they are high-quality lithium brine deposits.

2.2. Western Plateau of North America

The lithium-rich brine deposits in North America are primarily distributed in the Western Plateau region of the United States, including Clayton Valley, Searles Lake, the Great Salt Lake, and other deposits (Fig. 5). Furthermore, the

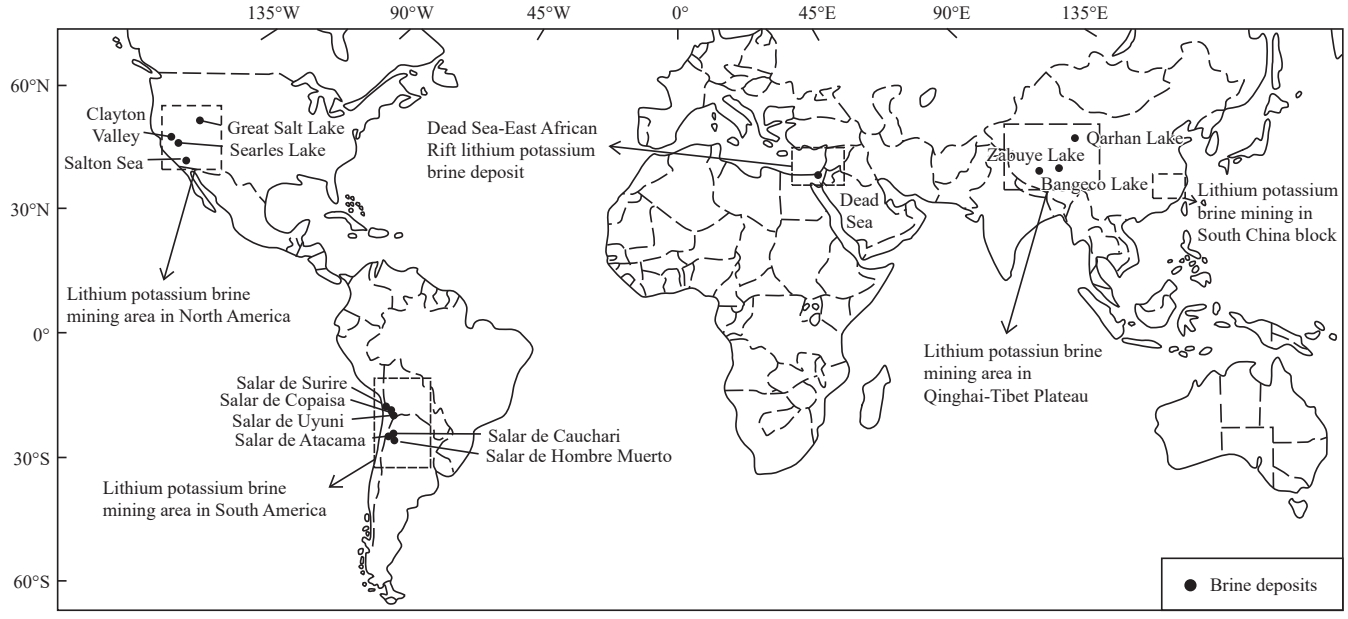

Fig. 3. Distribution map of major lithium-rich brine deposits in the world.

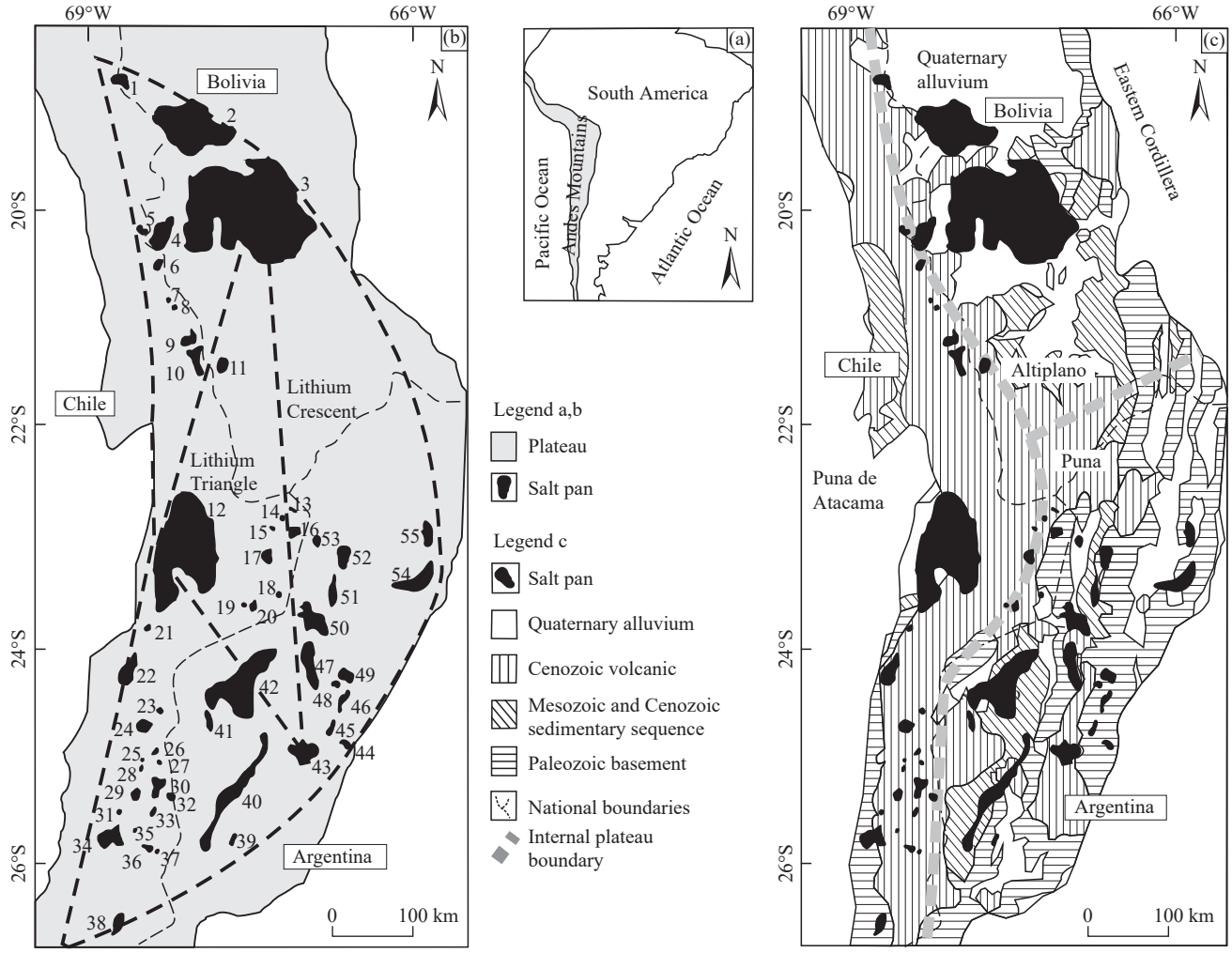

Fig. 4. Distribution and geological schematic map of salt lakes in the South American plateau (after Allmendinger R et al.,1997; López Steinmetz RL and Salvi S, 2021).

underground brine of the Salton Sea contains lithium resources. The brines of Clayton Valley and Great Salt Lake have elevations greater than 1000 m, followed by Searles Lake. The Salton Sea brines were primarily stored underground at depths of 1870 m and 3170 m. The overall elevation of the North American brine deposits is considerably lower than that of the South American plateau. The lithium concentrations of brines in Clayton Valley and Salton Sea are higher, averaging more than 160 mg/L. The lithium grades in Searles Lake and Great Salt Lake are close to the lowest industrial grade. The Mg/Li ratios of brines vary significantly. The Mg/Li ratios of the Great Salt Lake is 250, while those of Clayton Valley, Searles Lake, and Salton Sea are between 0.17 and 4.10 (Supplementary Table 3). These variations indicate distinct hydrochemical characteristics, suggesting potential differences in deposit genesis and geological influences and transformations in later periods of geological process.

2.3. Qinghai-Tibet Plateau

China's lithium-rich brines in salt lakes are primarily located in the Qinghai-Tibet Plateau region, including Tibet and the Qaidam Basin in Qinghai province, being the world's second-largest brine-type lithium resource distribution area after South America (Fig. 6).

There are more than 2000 lakes in Tibet, including about 500 salt lakes covering an area of 8225.18 km^2, which accounts for 30.46% of the total lake area in Tibet. The altitudes of most salt lakes ranges from 4300 m to 5000 m (Zheng MP et al., 2001). Salt lakes are primarily distributed on the northern and southern sides of the Bangong-Nujiang suture zones in northern Tibet, with small amounts also found in southern and eastern Tibet (Supplementary Table 4).

The Qaidam Basin comprises 37 lakes, with 30 of them being salt lakes. Most lakes are situated between 2700 m and 3000 m in elevation, such as Yiliping, East Tajinar, West Tajinar, Qarhan, Da Qaidam, Xiao Qaidam, Kunteyi, Dalangtans, and Gasikule Lakes (Supplementary Table 4; Zhu RZ et al., 1989; Wang A et al., 2016).

Compared with the plateaus of South and North America, the Mg/Li ratio of brines on the Qinghai-Tibet Plateau is generally higher, ranging from 23.07 to 199.19, with an average of 78.98, and reaching up to 517.34 in Qarhan Salt Lake, except for the extremely low Mg/Li ratios of Zabuye (0.01) and Dangxiong Co (0.36) (Supplementary Table 4).

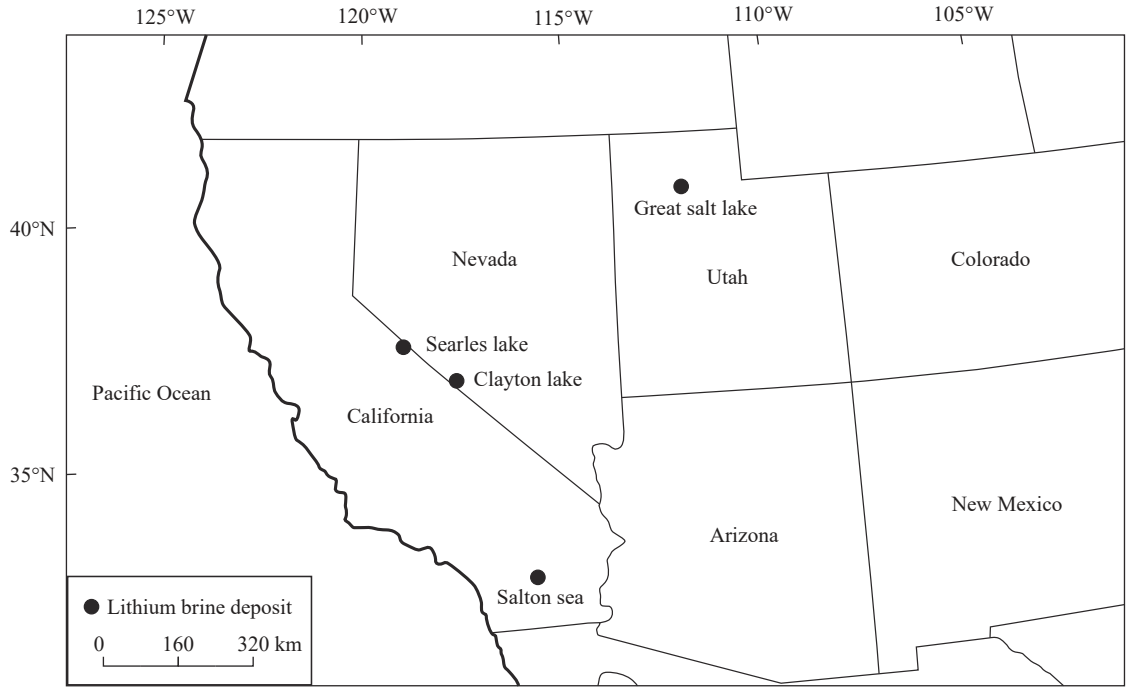

Fig. 5. Distribution map of brine-type lithium deposits in the western plateau of North America .

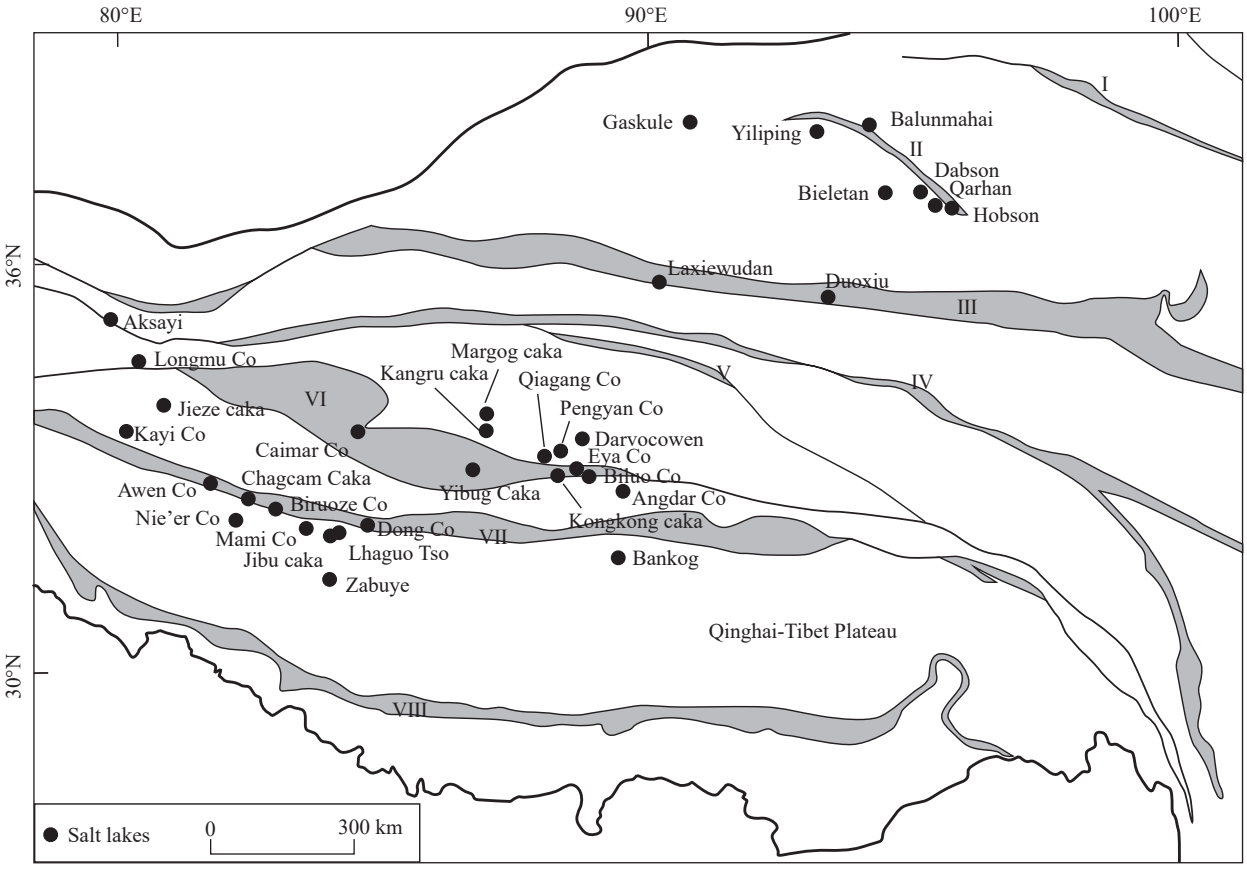

Fig. 6. Distribution map of lithium-bearing salt lakes in the Qinghai-Tibet Plateau (after Dong T et al. 2015, He L et al. 2015, Bai YM et al. 2018, Fan QS et al. 2018, Han JB, 2018, Li QK et al. 2022, Yu SY et al. 2022).

2.4. South China

Since the Mesozoic era, under the influence of an extremely arid climate, dozens of evaporite basins have formed in South China. Examples include the Jianghan, Jitai, Hengyang, and Qingjiang basins. The underground brine lithium deposits have been discovered in the Jiangling and Qianjiang depressions of the Jianghan Basin and the Jitai

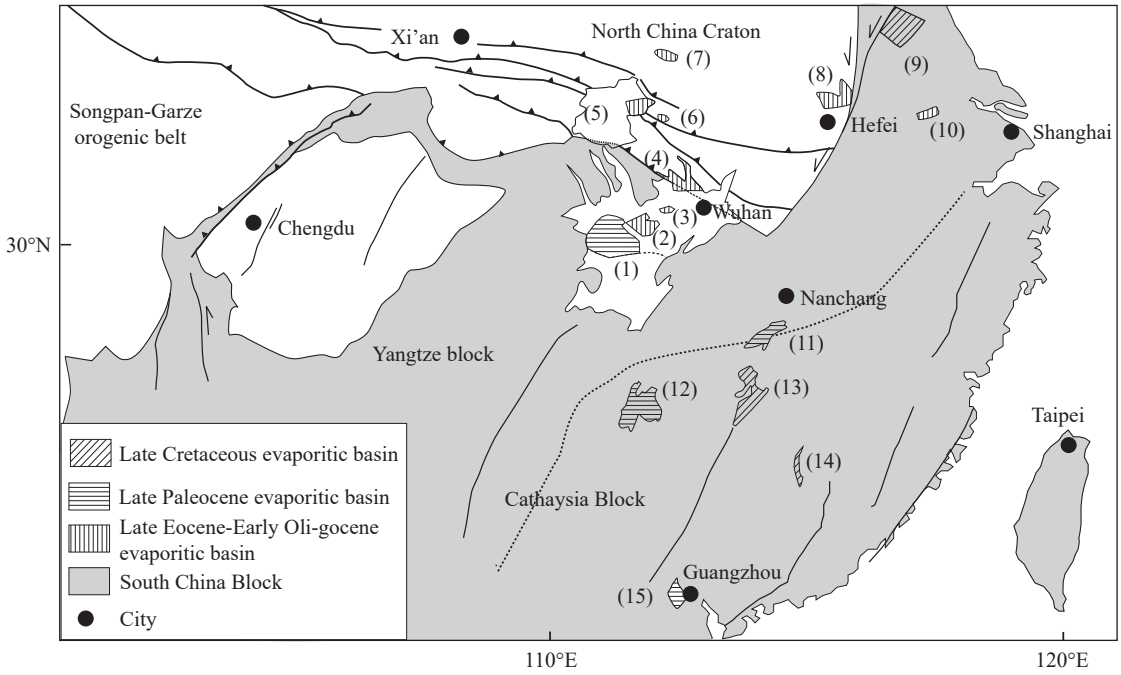

Fig. 7. Distribution map of evaporite basins in South China since Mesozoic. (1) Jiangling depression; (2) Qianjiang depression; (3) Xiaoban depression; (4) Yunying depression; (5) Nanxiang basin; (6) Yewu depression; (7) Wucheng Basin; (8) Dingyuan depression; (9) Huaian depression; (10) Jintan Basin; (11) Qingjiang Basin; (12) Hengyang Basin; (13) Jitai Basin; (14) Huichang Basin; (15) Sanshui Basin (modified from Wang JY et al., 2021).

Basin in recent years (Fig.7; Liu CL et al., 2013, 2016, 2021; Wang CL et al., 2020; Wang CL et al., 2021b). The Jianghan Basin covers an area of 36360 km^2. Under the influence of faults, the basin is divided into seven depressions and five uplifts. In the basin, brine exists on a large scale in Jiangling depression (6500 km^2) and Qianjiang depression (2500 km^2) (Supplementary Table 5).

The lithium concentrations in brines in the Jianghan Basin range from 25 mg/L to 182 mg/L, with the highest Mg/Li ratio being 3.67. In contrast, the lithium concentration of brines in the Jitai Basin is higher, but the basin area is smaller than that of the Jianghan Basin, and the Mg/Li ratio is 1.01 (Supplementary Table 5). In general, the Mg/Li ratios in the brines of the Jianghan and Jitai Basins in South China are low, similar to those of the South American and North American plateaus. The estimated resources of underground brine, managed through engineering in the Jiangling Depression integrated exploration district, amount to 1.209 Mt (Li_2O). Meanwhile, the predicted lithium resource (LiCl) of brine obtained from the Qianjiang Formation in the Qianjiang Depression is 3.5 Mt (Institute of Mineral Resources, Chinese Academy of Geological Sciences, 2011, 2013).

2.5. Siberian Platform

The formation and origin of the underground brine in the Siberian Platform remain unknown. There are many different ideas, related not only to the unique chemical composition of the brine and the high salinity of the groundwater but also to its distribution over large areas of the oldest plates of the Earth's continental crust. The Siberian Platform covers an area of over 4.4 million km^2, and the brine-rich areas are divided into the Angara-Lena, Tunguska, Yakutian, and Olenek artesian basins (ABs) regions (Fig. 8). The brines in the Angara-Lena, Tunguska, and Yakutian ABs are predominantly located in the evaporite strata of the Cambrian. In contrast, the brines in the Olenek ABs are mainly present in the Upper Proterozoic-Middle Cambrian and non-saline aquifers of the Upper Cambrian, with some also found in the Kimberley pluton. The brines have different salinities; the overall salinity varies from 195 g/L to 630 g/L, and the lithium concentrations in the brine section range from 33.5 mg/L to 480 mg/L (Alekseeva LP and Alekseev SV, 2018; Alexeev SV et al., 2020).

3. Geological characteristics of brine type lithium deposits

3.1. Brine type lithium deposits in salt lakes of the plateaus

Brine lithium resources in salt lakes are currently concentrated in North America, South America, the Tibetan Plateau, and other high-altitude areas where the climate is arid. Evaporation rates are much higher than precipitation, creating natural conditions for the enrichment of lithium and other useful elements. Most of the salt lakes are surrounded by Paleocene to Quaternary strata. The dry salt flats and salt lakes are exposed to the atmosphere, obviously affected by the current climate, precipitation, and evaporation. These factors are reflected in the fluctuating concentrations of the useful elements in the brines.

3.1.1. South-American-Plateau lithium deposits

Brine lithium deposits in the Andean Plateau of South America are typically characterized by high elevations, high

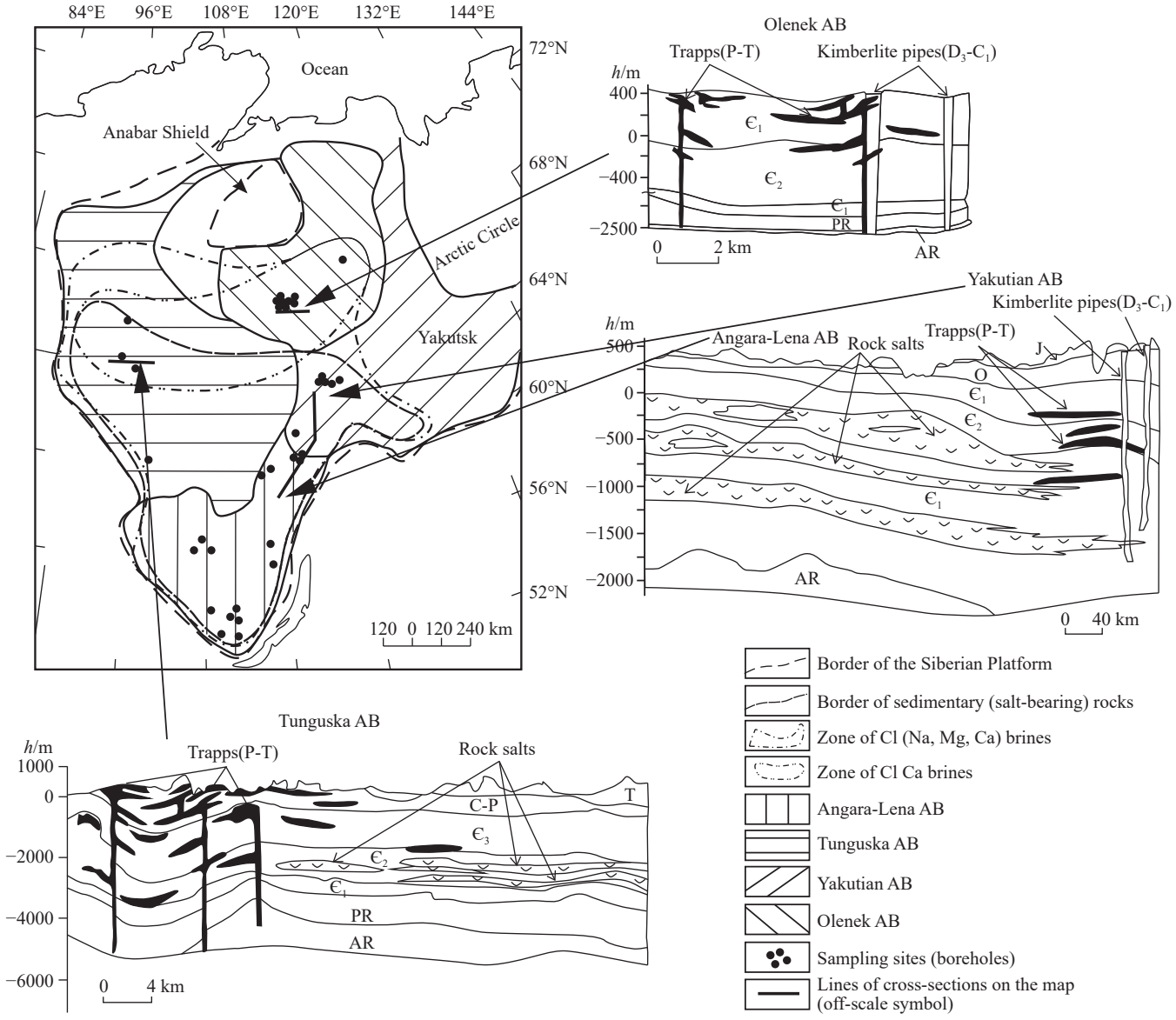

Fig. 8. Location map of the Siberian Platform and four artesian basins indicating distribution of salt-bearing deposits and brines on the Platform (after Alexeev SV et al., 2007).

lithium grades, and low Mg/Li ratios (Kampf SK et al., 2005; Vinante D and Alonso RN, 2006; López Steinmetz RL et al., 2018, 2020; Liu CL et al., 2021). Except for Atacama, which has a lower elevation of 2305 m, all salt lakes have elevations above 3300 m. The Uyuni salt lake has the largest area (10580 km^2) and the largest global lithium reserves. The lithium concentration of the brine ranges from 316 mg/L to 602 mg/L, with an average of 350 mg/L. The Atacama salt lake covers a saline area of approximately 3000 km^2, with an estimated volume of rock salt ranging from 1500 km^3 to 2200 km^3. The salt deposits are approximately 900 m thick, with a lithium concentration of up to 1400 mg/L (Gruber PW et al., 2011). The Hombre Muerto salt lake has attracted broad attention and has been exploited due to its vast reserves and high lithium concentration. In addition to highland saline lake-type brine deposits, geothermal brines have been found in El Tatio, Chile (Cortecci G et al., 2005).

The surrounding rocks of the Uyuni and Coibasa salt lakes in Bolivia consist mainly of Cenozoic andesite, rhyolite, felsic tuffs, and Quaternary alluvial deposits, which exhibit a high lithium concentration. The lithium-rich salt crust in the Salar de Uyuni varies in thickness from less than 2 m at the edge of the salt layer to approximately 11 m in the center (Risacher F and Fritz B, 1991). Boreholes drilled in the central part of the Uyuni salt lake encountered 11 salt layers with a total thickness of 80 m and at a depth of 121 m.

The Atacama salt lake in Chile are surrounded by a geological setting characterized by Paleozoic to Triassic volcanic-sedimentary rocks, Cretaceous-Neogene sedimentary rocks, Miocene felsic tuffs, accompanied by the intrusions of intermediate-acidic intrusive rocks, and salt marshes containing abundant salt cores within the salt lake (Garcia-Valles M et al., 2016). Lithium-rich brines are primarily used in the 3000 km^2 salt lake, with rock-salt covering an area of 1400 km^2. Gruber PW et al. (2011) preliminarily estimated that the Atacama Salt Lake hosts 6.3 Mt of lithium reserves

(Fig. 9).

The lithologies around salt lakes primarily include Paleozoic Cambrian crystalline basements in Argentina; Lower and Middle Ordovician metamorphic rocks, metamorphic sedimentary rocks, and volcanic rocks; Mesozoic terrestrial source clastic rocks; Cenozoic sedimentary rocks and volcanic rocks; and Quaternary alluvial fans, lacustrine phases, and salt sediments found near the periphery and within the interior of the salt lakes. In general, numerous Cenozoic intermediate-acidic extrusive rocks are found around salt lake. The lithologies are primarily composed of rhyolite, tuff, and felsic tuff, with minor quantities of dacites, andesites, and basalts (Seggiaro RE, 2013). These rocks have a high concentration of lithium, making them a valuable and abundant source of lithium for salt lakes.

3.1.2. Brine deposits in western plateau of North America

Clayton Valley, Nevada, is a medium-scale canyon in the western United States, with a dry salt basin covering approximately 100 km^2 within a 1300 km^2 surface convergence area. The elevation rises from 1300 m in the dry salt basin to Piper's Peak at 2880 m in the Silver Peak Range. Late Neoproterozoic to Ordovician carbonate and clastic rocks form the basement rocks, while the upper part consists of late Miocene to Pliocene tuffaceous lacustrine deposits, with tuff and rhyolite as the predominant lithologies. The uppermost part consists of Quaternary alluvial fan, dunes, loose and wet salts, silt, and sand (Fig. 10). The Cenozoic stratigraphy demonstrates the formation of lacustrine facies mud deposits alternating with salt layers under the influence of alternating climate fluctuations (Kunasz IA, 1974; Davis JR et al., 1986; Price JG et al., 2000; Araoka D et al., 2014; Munk LA et al., 2016; Lowenstein TK et al., 2016, 2017).

Located in a closed basin in eastern California, USA, Sears Lake is a contemporary ephemeral alkaline salt lake with significant deposits, including trona, rock salts, and so on. Searles Lake is the third of the five lakes recharged by the Owens River. During periods of drought climates, the Owens River flows into Searles Lake through the Owens and China Lakes, contributing to the deposition and accumulation of evaporites (Lowenstein TK et al., 2016). The Searles Lake contains at least two aquifers: an upper aquifer to a depth of 20 m that has Li average concentration of 150×10^{-6} (Wt.) ,

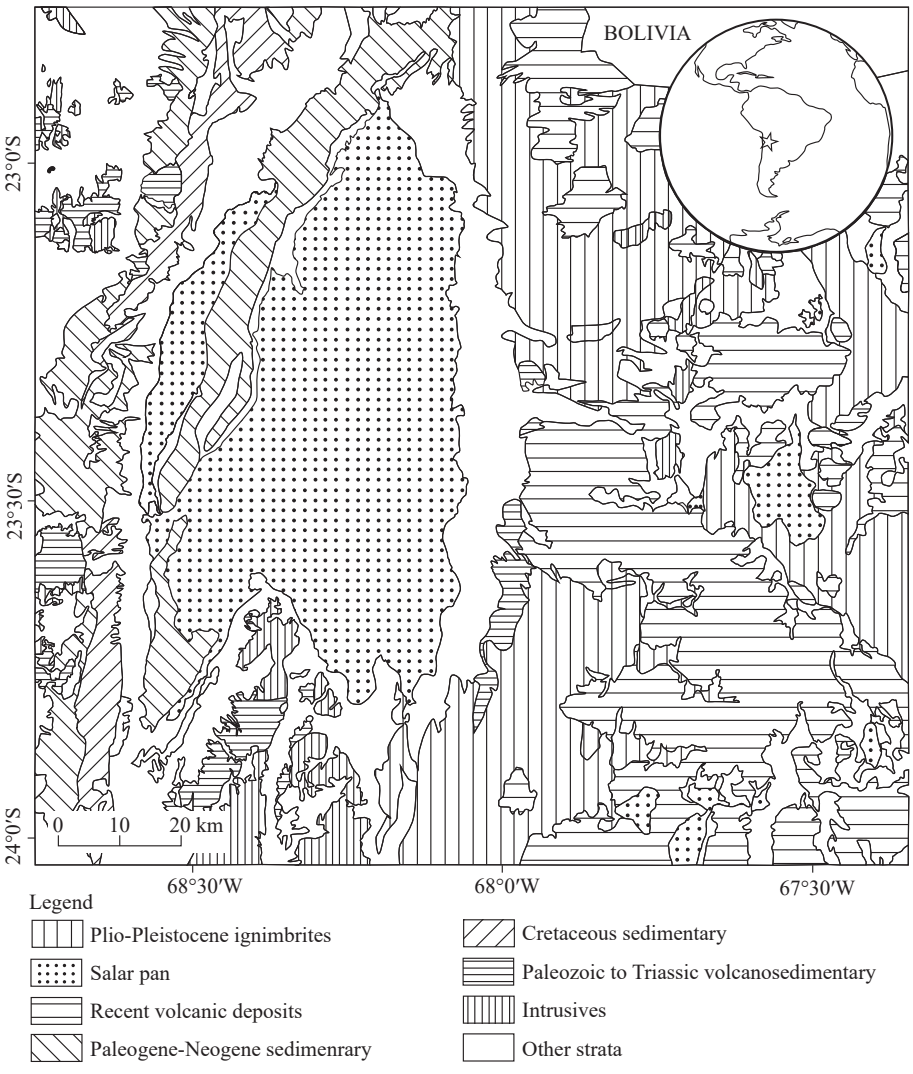

Fig. 9. Map of the Salar de Atacama basin, showing the major rock units (Godfrey LV et al., 2019).

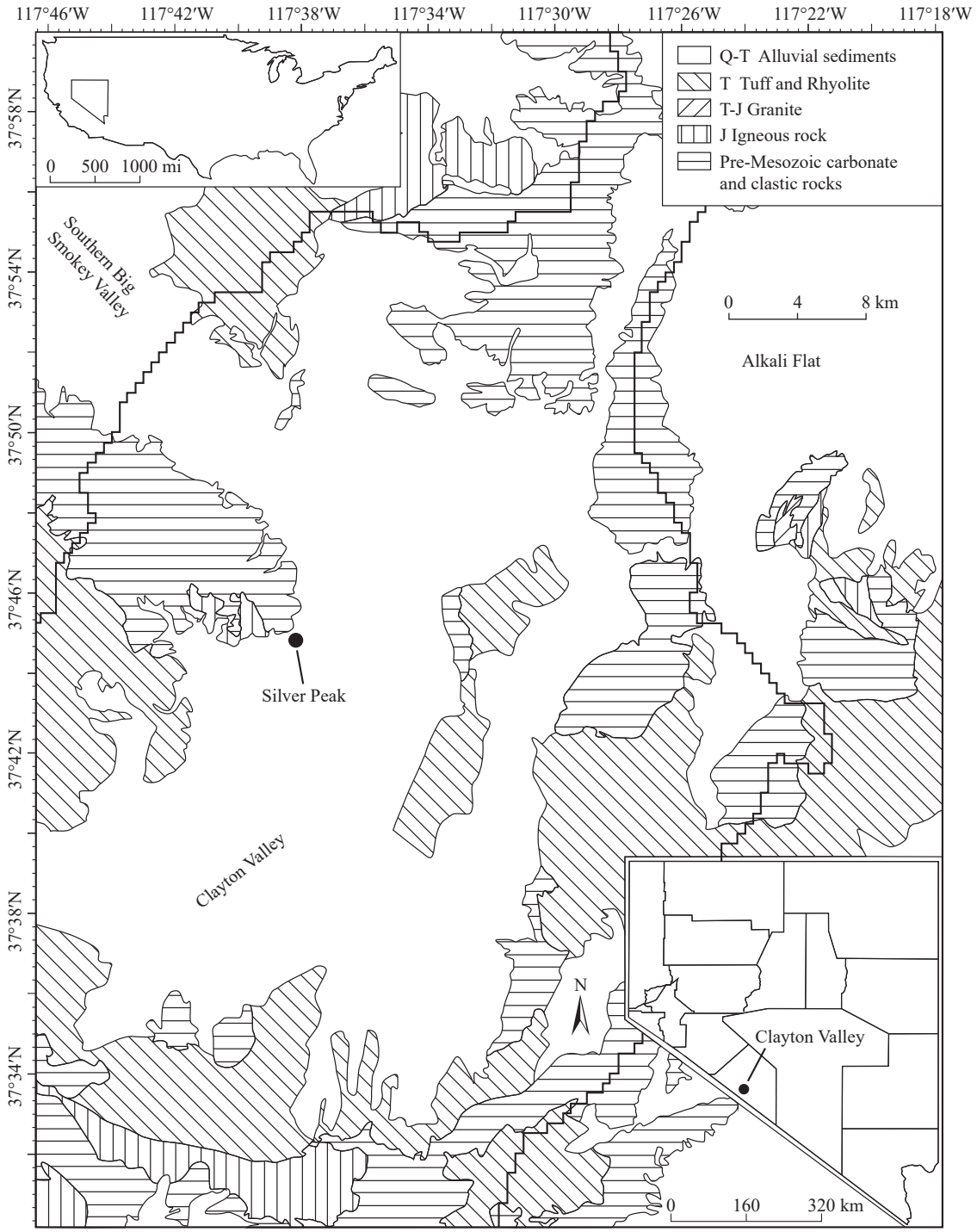

Fig. 10. Regional geology of the Clayton Valley, NV region represented by USGS geologic map (afterLudington S et al., 2007).

and a second aquifer beneath a 3–5 m thick clay layer that contains an average Li concentration of 60×10^{-6} (Wt.).

In Salton Sea, there is a geothermal brine deposit discovered in the 1960s during scientific drilling in southeastern California. The rocks exposed on the surface are primarily Paleozoic metamorphic sedimentary rocks and Pleistocene volcanic rocks. The drilling encountered high-temperature (270–370°C) hot brines at depths of 1865–1877 m and 3170 m. These hot brines are rich in K, B, Li, Rb, Cs, and heavy metals such as Fe, Pb, Zn, and Cu (Thompson JM and Fournier RO, 1988). The concentrations of Cu, Zn, and Fe in these brines are dozens to hundreds of times higher than those in the usual salt lake brines, characteristic of geothermal brines originating from deep Rift Valleys. Other salt lakes in North America, such as the Great Salt Lake in the United States, have lithium concentrations of ranging from 100 mg/L and 200 mg/L (Butts D, 1975).

Researchers have also discovered oilfield brines in numerous oilfields. These include the Smackover Formation in the northern Gulf Coast Basin (Collins AG, 1976) and the Beaverhill Lake Formation in Alberta, Canada.

3.1.3. Brine lithium deposits of Qinghai-Tibet Plateau

According to Song PS and Xiang RJ (2014), the LiCl reserves in salt lakes on the Tibetan Plateau can reach 23.3 Mt. The main salt lakes are Zabuye, Chagcam Caka, Dangxiong Co, and Eyacuo, with salinity between 50 g/L and 350 g/L. In the brines, there is a wide range of high-value elements like Li, K, B, Rb, and Cs, and the concentration of lithium ion can range from 50 mg/L to 1500 mg/L. Most salt lakes with a lithium concentration of more than 200 mg/L are concentrated near Bangong-Nujiang Suture Zone. Low Mg/Li ratios and high Li concentrations characterize brines in salt lakes, and the brine chemistry type is primarily the carbonate-sulfate type (Lian YQ and Guan HZ, 1994; Han FQ, 2001; Zheng MP et al., 2001; Zheng XY et al., 2002; Cao WH and Wu C, 2004; Zhao YY et al., 2005; Liu XF et al., 2007; Song PS and Xiang RJ, 2014; Shi LJ and Wang M, 2019; Li QK et al., 2022).

Carbonate-type salt lakes in Tibet are Zabuye and Dangxiong Co called as representative salt lakes (Li ZY et al., 2024). Permian clastic rocks, carbonate rocks, Cretaceous volcanic-sedimentary rocks, Paleoproterozoic terrestrial clastic-volcanic rocks, Neoproterozoic volcanic-clastic rocks, Quaternary residual slope products, and fluvial and lacustrine deposits can be observed in the exposed strata around Zabuye Salt Lake (Fig. 11). The salt lake consists of two parts, with the northern sub-basin being a 98 km^2 brine lake containing saturated brine. The brine depth is around 0.7–2 m, and it has a lithium concentration of about 1500×10^{-6} (Wt.). The southern sub-basin is a semi-arid salt lake, covering an area of approximately 145 km^2 (Nie Z et al., 2010). In a borehole drilled in the northern part of the sub-basin to a depth of 84 m, the upper 6 m of the cores contained carbonate, sulfate, and borate minerals as well as 1% Li_2CO_3, indicating a good potential Li resource. The lithium reserve in Zabuye is approximately 1.5 Mt. However, according to the lithium concentration, the lithium reserve in the surface saline lake is only 0.2 Mt. Therefore, it is hypothesized that in addition to the surface saline lake, lithium-rich brines may exist in the shallower part of the lake, which is yet to be confirmed by further work (Gruber PW et al., 2011).

The average lithium concentration of the brines in the Dangxiong Co Salt Lake is 430×10^{-6} (Wt.). Most of the brines on the Tibetan Plateau are distributed as salt intergranular-pore brines at the surface and in the shallow range of a few meters, whereas some are at depths below a few tens of meters. Within the salt lakes of the Qaidam Basin, there are mostly synclinal deposits within the Paleoproterozoic-Neoproterozoic syngenetic deposits within the anticline, and the lithologies are primarily evaporite deposits of rock salts, sulfates, and borates with local depths of up to 1000 m (Han FQ, 2001).

Yiliping Salt Lake is located in the middle of Qaidam Basin, with a total area of about 1500 km^2. It is a dry salt lake, mainly supplied by Nalengele River and Taijinar River in the southeast of Qaidam Basin (Yu JQ et al., 2018). The hydrochemical type of brine is magnesium sulfate subtype, and the concentrations of LiCl are between 1300 mg/L and 3000 mg/L. West Taijinar Salt Lake is about 2680 m above sea level. The area is about 560 km^2, the hydrochemical type of brine is magnesium sulfate subtype, and the salinity is 334.6–336.3 g/L. LiCI content is higher than 3000 mg/L. East Taijinar Salt Lake is a closed lake basin surrounded by hills on three sides, with an area of about 350 km^2 with altitude ranging from 2683.9 m to 2684.5 m. The brine lithium is stored in the rock salts crystals in the upper and lower layers, and the hydrochemical type is mainly magnesium sulfate type, with a salinity of 330.0–333.9 g/L. The lithium concentration in pore water of loose clastic rocks is 324.0–428.0 mg/L. The

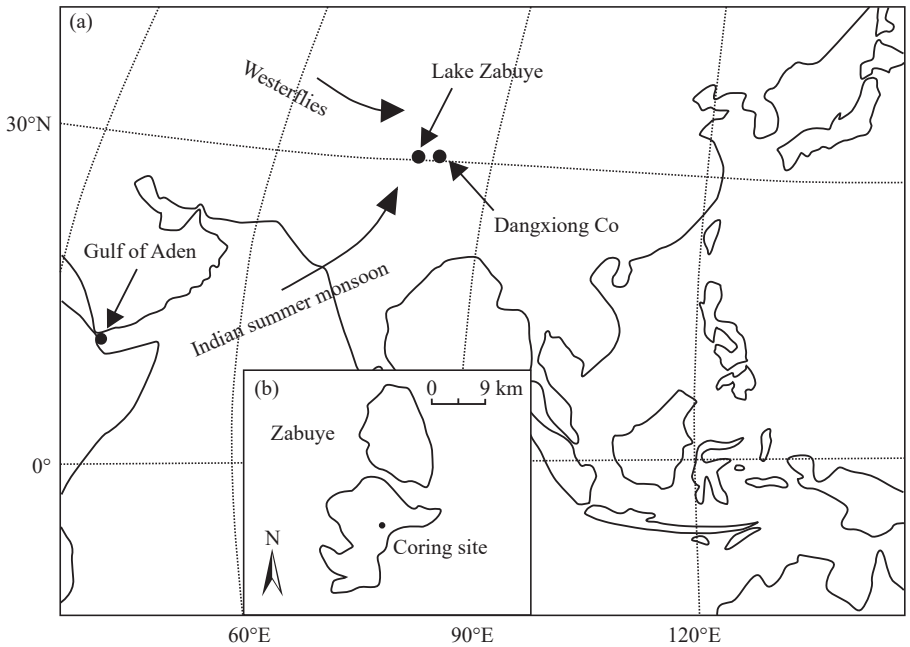

Fig. 11. a–Location of Lake Zabuye in the world. http://visibleearth.nasa.gov; b–map of the southern and northren subbasins of Zabuye (after Ling Y et al., 2017).

Li content of intercrystalline brine is between 720 mg/L and 980 mg/L. The Li content of intercrystalline confined water is generally 560–1100mg/L (Han JB, 2018). Qarhan Salt Lake has an area of 5856 km^2, which is the second largest quaternary salt lake in the world after the Uyuni Salt Lake in Bolivia, South America. From west to east, it is divided into four sections: Bieletan, Dabsan, Qarhan, and Huobuxun. The chemical type of brine is mainly chloride type, and the concentration of lithium in intercrystalline brine can reach 46.5–124 mg/L (Han FQ, 2001; He L et al., 2015).

3.2. Underground brine-type lithium deposit

3.2.1. Underground brine lithium deposits in South China

The underground brine-type lithium deposits have been discovered in the Jianghan Basin in South China (Dai SZ and Fang ZX, 1994; Huang H et al., 2015; Liu CL et al., 2013, 2016, 2017). Brine deposits are distributed in the South China Block, which was formed by the collision of the Yangtze and Cathaysia Blocks during the Neoproterozoic (Shu LS, 2012). During the Cretaceous–Paleogene period, due to the collision and convergence of the Pacific Plate and the Indian Plate on the Eurasian Plate, the South China Block underwent a transformation of the tectonic system from the EW to the NNE-NE direction and the conversion of the extrusion to the extensional stress regime (Ren JS et al., 1980, 1990), and several fracture systems of different grades and scales were formed. Against the background of the aforementioned plate tectonic movement, dozens of terrestrial basins were developed in southern China (Fig. 4), including the Jianghan, Hengyang, Jitai, Huichang, and Ganzhou basins (Yao QC and Lou JS, 2008; Wang CL et al., 2013a, 2013b). Under the control of an arid climate, a large amount of evaporites, such as gypsum and rock salt, were deposited in the basins (Liu Q et al., 1987; Wang CL et al., 2012, 2015, 2018, 2021a, 2021b; Liu CL, 2013; Liu CL et al., 2013, 2016; Ma LC et al., 2015; Shen JJ et al., 2015). The lithium brine deposits have been found in the Jianghan and Jitai Basins in South China (Pan YD et al., 2011; Liu CL, 2013), and the brines are rich in Li, K, B, Rb, Cs, and Sr, which are known as composite deposits (Liu YH and Deng TL, 2006; Liu CL et al., 2016, 2017). Liu et al. (2016, 2021) suggested that terrestrial salt lakes had

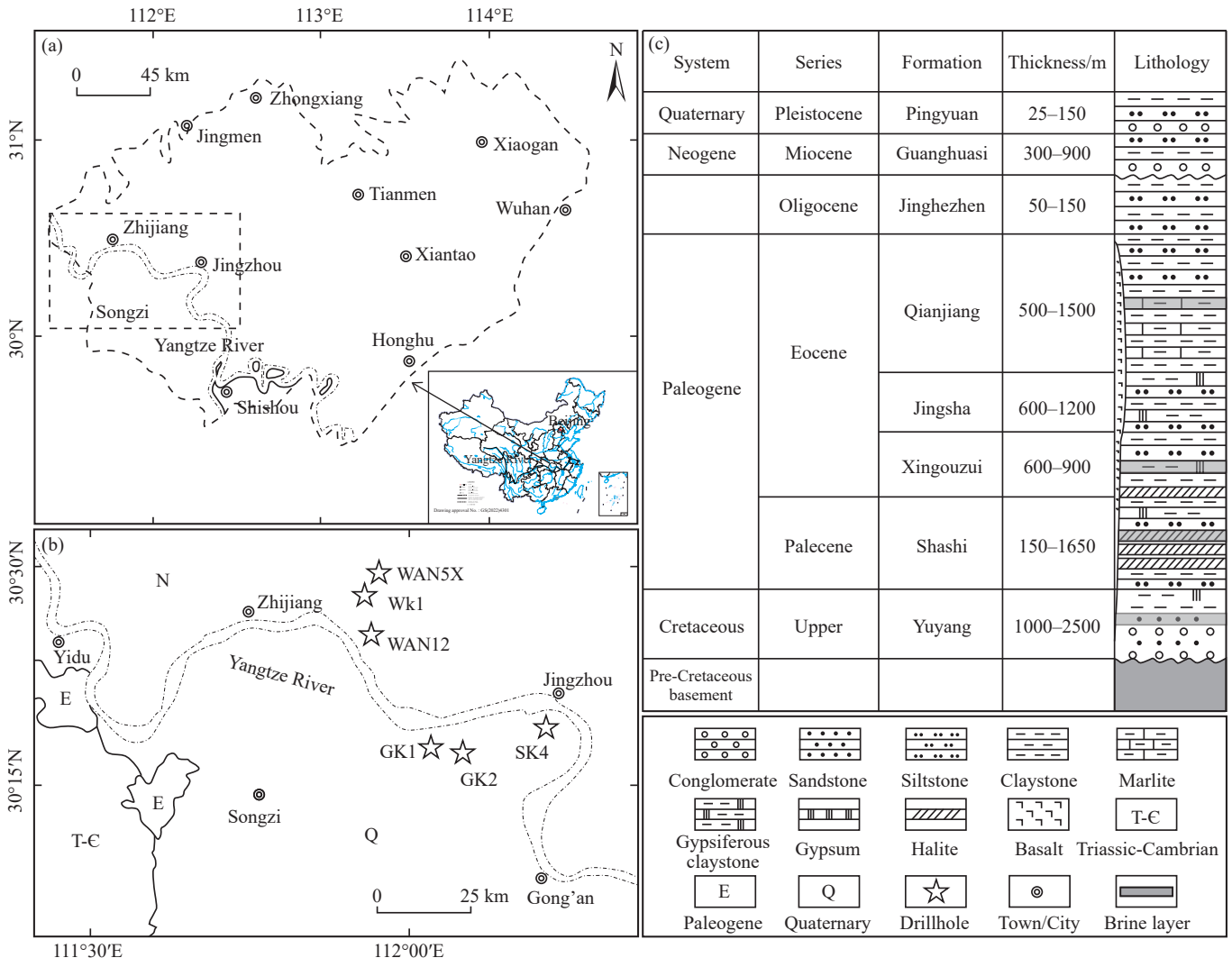

Fig. 12. a–Geographic location of the Jianghan Basin (after Gan YQ et al., 2014); b–locations of sampling boreholes (after Yu XC et al., 2021); and c–stratigraphic column of the Jianghan Basin (after Wang BJ et al., 2006).

existed in South China during the Cretaceous-Paleogene period and that ancient salt lake brine lithium deposits were formed broadly in this region.

(i) Jianghan Basin

Geotectonically, the Jianghan Basin is located at the intersection of the northeast-oriented rift system (Neo-Cathaysian Rift System) and the east-west-oriented Central Yangtze Block, accompanied by large-scale volcanic activities. It has experienced multiple tectonic movements, such as faulting, subsidence, breaking depression and subsidence, which together constitute a fault-slip basin. The main deposits in the basin are the Upper Cretaceous Honghuatao and Yuyang formations; Paleocene Shashi Formation; Neocene Xingouzui, Jingsha, and Qianjiang formations; Oligocene Jinghezhen Formation; Neogene Miocene Guanghuasi Formation; and Quaternary Pleistocene Plain Formation (Fig. 12). The Shashi, Xingouzui, and Qianjiang formations are primarily salt-lake deposits, corresponding to the two salt-forming cycles in the basin. Lithium-rich brines have been found in the lower part of the Shashi and Xingouzui formations of the Jiangling Depression and the Qianjiang Formation of the Qianjiang Depression, which are also rich in K, Rb, Sr, Cs, Br, I, B, and so on, reaching the level of industrial and comprehensive utilization, with huge potential resources.

They are typical underground brine-type lithium deposits, which are considerably different from salt lake deposits in the plateaus in terms of brine occurrence and genesis. Brines are generally stored at depths of more than 2000 m. For example, the brines in the Jiangling and Qianjiang depressions are primarily stored in volcanic pores, mudstone fissures, and sandstone pores below 3000 m, and no salt lakes developed on the surface. The shallow brine in the Jitai Basin is primarily stored in mudstone fissures and fractures at a depth of more than 200 m below the ground surface. The brines have little connection with the ground and are predominantly influenced by the ancient salt lake environment and subsequent diagenesis. The results of brine sample analysis in Jiangling Depression boreholes (Yan K et al., 2022) show that the salinity of brine range from 114.00 g/L to 347.50 g/L, with an average of 227.62 g/L. The concentrations of lithium are 27.20–97.85 mg/L, with an average of 49.21 mg/L. The results of brine sample analysis in Qianjiang Depression show that the salinity of brine ranges from 125.70 g/L to 347.00 g/L, with an average salinity of 282.75 g/L. Lithium concentrations are 25.53–182.00 mg/L, with an average of 67.12 mg/L (Yu XC et al., 2022).

(ii) Jitai Basin

The Jitai Basin is a rhombus half-shaped basin controlled by several major faults. The main basin-controlling faults are the northeast-oriented Yongchuan-Xiajiang, Suichuan-Dexing, and Ganjiang faults, followed by the northwest-oriented Jishui Fault (Yu XQ et al., 2005). The basin is also influenced by secondary fractures. From north to south, it is divided into a few secondary tectonic units, that is the Ji'an, Zaohe, Gaopi-Meigang low-uplift, and Taihe depressions. Each of these secondary tectonics is further subdivided into smaller tectonic structures, such as the Xinwei and Datang depressions. These subdivisions reflect the complex characteristics of the development of the different tectonic phases that have been superimposed on each other in the basin. The brine is primarily deposited in a set of lacustrine sedimentary strata in the third lithological section of the Upper Cretaceous Zhoutian Group. The lithology consists of caesious-banded gypsum-bearing calcareous mudstone interspersed with purplish-red calcareous mudstone and several layers of rock salt. Additionally, it contains more stellate, massive, banded gypsum, and anhydrite. The brine salinity in the boreholes in Jitai Basin range from 177.47 g/L to 326.64 g/L, with an average value of 293.38 g/L. The concentrations of Li range from 69.54 mg/L to 119.21 mg/L, with an average value of 103.18 mg/L. The hydrochemical type of brine is chloride type (Fu LL, 2017).

3.2.2. Siberian platform

The geological characteristics of the four basins and the occurrence of brine deposits on the Siberian platform are shown in Fig. 8. The Siberian platform contains a thick crystalline base of the Archean-Proterozoic, with quartzite, gneiss, schist, and amphibolite as the main lithologies. Siberian sedimentary rocks cover the Cambrian-Jurassic rocks, including Cambrian terrestrial carbonate and sulfate. Additionally, there are sedimentary layers of rock-salt and other evaporites, their minerals such as gypsum, anhydrite, and halite. The southern and western parts of the terrane include the Angara-Lena, Tunguska, Yakutian ABs, and Olenek AB (Alexeev SV et al., 2020). The Angara-Lena AB geological section contains rock-salt formations with a total thickness of up to 900 m (Vakhromeev AG, 2014) and is divided into lower salt, salt-bearing, and upper salt sections, with the thickness of each section ranging from 500 m to 2500 m. The geological characteristics of Tunguska AB are similar to those of the geological section of Angara-Lena AB, with the difference being the extensive distribution of trap cuts and layered intrusions. The thickness of the salt layer is only tens of meters, and the brines are primarily found at a depth of 500–3000 m, mostly in the terrestrial carbonate strata. The upper part consists of Carboniferous and Permian terrestrial carbonate strata, with a thickness ranging from 700 m to 1000 m, containing saline brines and fresh water. In the northern part of the platform (including Olenek AB), the sedimentary cover is mainly composed of terrestrial Cambrian carbonates. At depths greater than 2500 m, there is a Paleozoic crystalline basement. The Cambrian sediments consist of dolomite, tuff, muddy tuff, clayey tuff, and sandstone. Unlike the Siberian Platform, Olenek AB does not have thick rock salt layers.

The brines of the Angara-Lena, Tunguska, and Yakutian in the lower salt and salt-bearing sections were primarily found in the salt-bearing strata of the Upper Proterozoic to Upper Cambrian. The salinity of the saline of the Angara-Lena, Tunguska, and Yakutian ranges from 270 g/L to 631

g/L (average 500 g/L), 80 g/L to 550 g/L (average 380 g/L), and 169.8 g/L to 444.6 g/L (average 404 g/L), respectively. The lithium concentration ranges from 0.21 g/L to 486 mg/L (average 115 mg/L), 0.28 g/L to 837 mg/L (average 243.2 mg/L), and 5.8 mg/L to 90.5 mg/L (average 39.1 mg/L), respectively. Olenek ABs have abundant non-saline strata and contain two aquifers, of which the Upper Proterozoic and Lower–Middle Cambrian have salinity of 195.8–411 g/L (mean 328.0 g/L) and Li concentrations of 34.1–415.3 mg/L (mean 183.4 mg/L); the salinity of the Upper Cambrian aquifer ranges from 31.1 g/L to 252.2 g/L (mean 92.0 g/L) and Li concentrations of 3.1–120.8 mg/L (average 33.3 mg/L). Lithium carbonate reserves are predicted to reach 24,200 tons (Alexeev SV et al., 2020).

Alexeev SV et al. (2020) analyzed the correlation of lithium concentrations with depth and salinity in the four regions mentioned above and concluded that there is a significant correlation between Li concentrations and the depth of the saline aquifer only in the Olenek AB basin. In all basins, the correlation between Li concentrations and groundwater TDS was more pronounced; the higher the groundwater salinity, the higher the Li concentration.

Zherebtsova IK and Volkova NN (1966) showed that seawater evaporates at Li concentrations of up to 30 mg/L. In contrast, the concentration of Li is ten times higher than natural brines consisting of Na-Ca and Ca chloride ions than in fresh groundwater (Alexeeva LP and Alexeev SV, 2018). Therefore, the presence of lithium in groundwater is attributed to the interaction of the water-rock system during the formation of the present-day brine composition. The general trend of increasing of lithium concentrations in brines with a decreasing of Na/Cl ratio suggests that water-rock interaction is one of the key mechanisms responsible for the changes in groundwater composition, resulting in lithium enrichment within closed hydrogeological systems.

3.2.3. Other areas

Lithium-rich brines are found in portions of petroleum reservoirs such as the Smackover (Prather BE et al., 2023), Wyoming (Morgan LA et al., 2023), Oklahoma (Symcox C and Philp RP, 2023), Texas (Williams AK et al., 2017), Arkansas (Chapman CR et al., 1988), and North Dakota oil field brines (Nancy EL et al., 2016), with concentrations up to 700 mg/L (USGS, 2023).

3.3. Geothermal spring water type lithium deposits

Geothermal spring-type brine lithium deposits accounts for approximately 3% of global lithium resources. The heated fluids pass through lithium-rich geologic bodies and undergo a water-rock exchange reaction, leading to the formation of fluids that are rich in lithium, boron, potassium, and other elements. Additionally, this process results in the formation of lithium-rich brine deposits in suitable tectonic enclosures within the reservoir body (Tan HB et al., 2016, 2020; Fan QS et al., 2018).

The geothermal brines are characterized by abnormally high temperatures and the presence of high thermal anomalies nearby. Examples of such deposits include the Gulu hot springs in the Naqu region of Tibet, the Yangbajing boiling spring water (Dong T et al., 2015), Wairaki in New Zealand, El Tatio in Chile, and Reykanes in Iceland (Ruff SW and Farmer JD, 2016; Antonio Pio R et al., 2022).

4. Analysis of metallogenic factors of brine-type lithium deposits

Brine-type lithium deposits worldwide are similar, but also different in terms of their geological features, state of existence, and mineralization mechanisms. In this study, we conducted a systematic investigation and comparison of the distribution of terrestrial brine-type lithium deposits both domestically and abroad. Our main focus was to explore the conditions and models of lithium mineralization in brines in the salt lakes.

4.1. Regional tectonic dynamics background

The intense activity between the oceanic and continental plates caused a significant difference in topographic elevation. The Cordillera Mountain system in North and South America was formed by a subduction collision between the Pacific Plate and the American Plate to form the present plateau landform (Xu ZQ et al., 2021). In addition to the North American plateau, being above 1000 m in elevation. The South America and Tibetan Plateau are above 2000–3000 m. The Qinghai-Tibet Plateau of China is called the 'roof of the world' because of the strong collision and orogeny between the Indian and Eurasian plates. Strong subduction of oceanic and continental plates, as well as continental plate colliding with continental plate controlled the sedimentary formation of clastic rocks, volcanic rocks, and evaporites in the continental margin (Allmendinger R et al., 1997; Baby P et al., 1997; Zhou XM and Li WX, 2000; McQuarrie N, 2002; Alonso RN et al., 2006). The subduction of the paleo-Pacific plate to the South China continent (Fig. 13, Zhou XM et al., 2000) controlled the formation of deep brine lithium deposits in Jianghan and Jitai basins in South China (Liu CL et al., 2016). On one hand, the Li-rich volcanic rocks provide a large amount of lithium for brine; deep active structures drive the rise of deep hot springs, which accelerates the water-rock interaction and brings more lithium; on the other hand, the arid evaporation environment enables the continuous enrichment of lithium in salt lakes. Plate activities can cause crust-mantle mixing or melting of crustal materials, resulting in the large-scale formation and upwelling of magmatic materials. The process can bring many metallogenic elements, such as Li, from the Earth’s interior, supplying a significant amount of lithium for brine deposits. Additionally, the high-altitude mountains block and limit the reaching of a large amount of water vapor, leading to higher evaporation rates in the plateau area. This results in an extremely arid climate, and further enrichment of Li in lake water. The strong action of tectonic movement can lead to the development of nearly

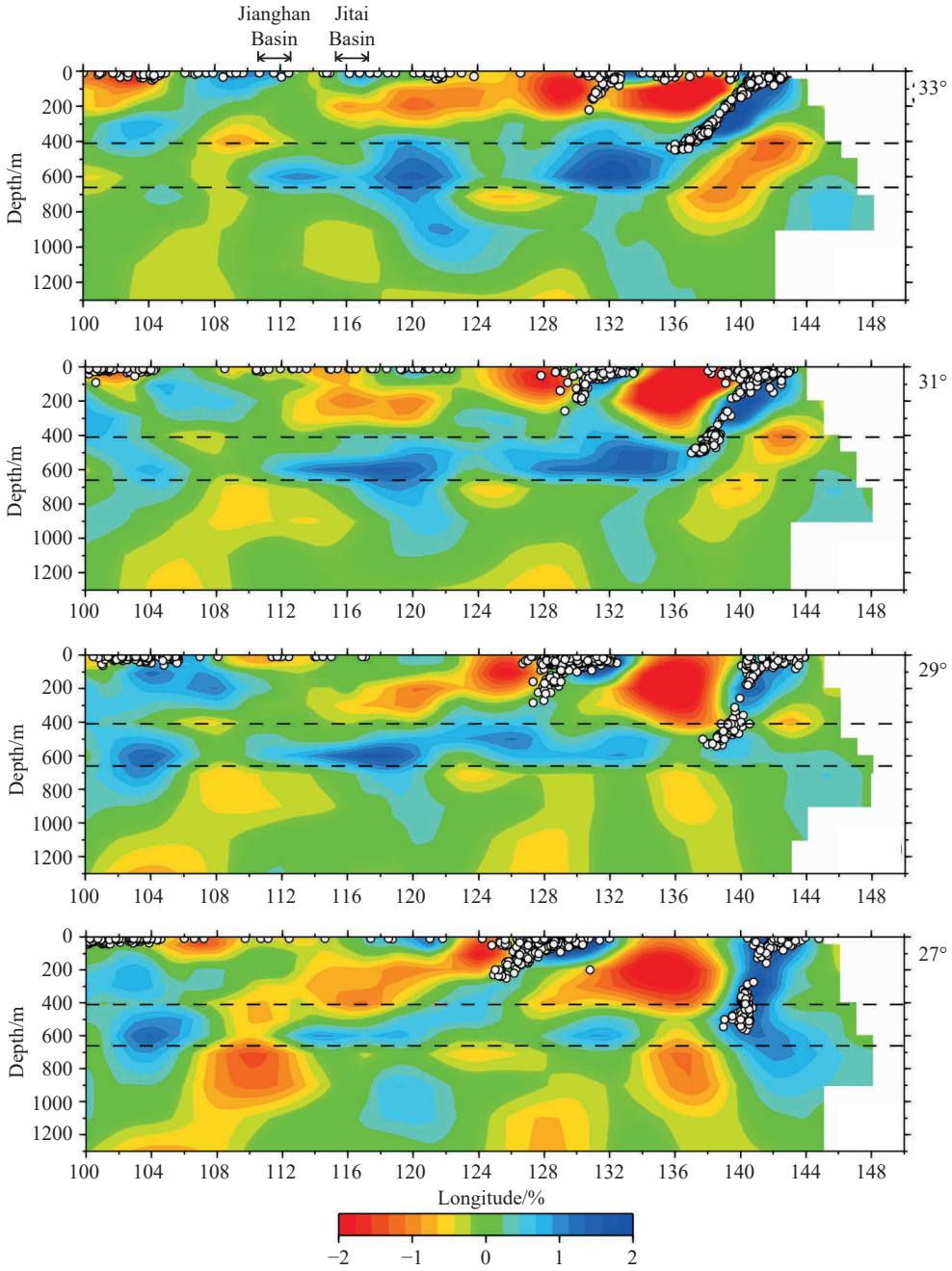

Fig. 13. Map of Pacific plate subduction into southern China plate and its stagnant slabs in the mantle transition zone during the late Mesozoic in southeast China (after Huang JL and Zhao DP, 2006).

north-south trending intermontane basins, which provide a closed reservoir environment for the migration and storage of brine. The large topographic height difference intensifies the weathering of the lithium-rich source rocks around the basins by surface and underground water bodies and causes surface runoff containing lithium to sink into the basin, providing metallogenic conditions for the enrichment, migration, and storage of lithium elements (Wang A et al., 2016).

4.2. Arid climate

Lithium-rich brine type deposits in Plateau salt lakes are primarily distributed in the tropical arid climate zone from 30° to 40° N latitude and 20° to 30° S latitude. In these areas, there exist abundant sunshine, high evaporation, low precipitation, and brines are exposed to the atmosphere. This makes them more susceptible to the influence of climate.

Information from the Chilean National Water Resources Agency (1987) in South America indicates that the Central Andes of South America is characterized by an arid climate, with drought running from east to west. It is also noted that the Coastal Range and the Central Valley are considered to be the driest in the world, with near-zero precipitation and a potential evaporation of 2500 mm/year.

The annual precipitation in the northern part of the Tibetan Plateau is 121 mm, and evaporation is 2423 mm (Zhao YY, 2003). The average annual evaporation (2302 mm) to precipitation (151 mm) ratio of Chagcam caka Salt Lake is

15.4∶1 (Zhao YY, 2003). The Yiliping Salt Lake area in the Qaidam Basin has scant rainfall, with an annual precipitation of 25 mm; however, evaporation reaches more than 3,000 mm, and large quantities of salt minerals, such as gypsum, sylvite, halite and picromerite, are deposited in the lake (Li BT et al., 2012). The ratio of evaporation to precipitation in the Qarhan Salt Lake area is (3456 mm: 28.1 mm) 123∶1 (Zheng MP, 1989).

At the end of the Mesozoic era, the Paleo-pacific plate subducted beneath the Asian continent, resulting in the formation of high coastal mountains in South China in the result, this geological process led to an arid climate (Chen PJ, 2000). An arid climate is a crucial factor in promoting lithium enrichment and eventual mineralization of brine deposits (Tong GB et al., 2002). For instance, in South China, the Jiangling and Qianjiang depressions in the Jianghan Basin have accumulated significant amounts of salt and gypsum deposits (Wang CL et al., 2012, 2013a). Additionally, the Jitai Basin exhibits rhythmic interbedding of gypsum rocks and lacustrine clastic sedimentary rocks, indicating a paleo-saline depositional environment influenced by the arid climatic conditions of that time. This suggests that the arid climate played a significant role in lithium enrichment.

The results of evaporation and precipitation of the three plateau salt lakes are shown in Supplementary Table 6. It can be seen that the precipitation ranges from 25 mm/y to 320 mm/y, with an average of 117.32 mm/y; the evaporation ranges from 783 mm/y to 3500 mm/y, with an average of 1825.88 mm/y; the average value of evaporation is 30 times greater than the precipitation (Supplementary Table 6), showing that the plateau salt lakes are generally in an extremely arid climate environment.

In the world, the distribution of terrestrial brine Li deposits are associated with extremely arid climates, which are particularly evident in the surface saline lakes of South America, North America, and the Tibetan Plateau. The extremely arid conditions on the plateaus increase the Li concentrations in shallow surface brines by two to three orders of magnitude compared to the Li-level values measured in major tributaries and hot water discharges. López Steinmetz RL and Salvi S (2021) studied twelve salt lakes in the southern part of the Puna Plateau, South America, and found a good correlation between Li concentration and TDS, suggesting that older basins have more time to store evaporation products than younger basins and that sustained evaporation has resulted in the effective enrichment of a variety of elements, including Li. In the absence of external water recharge or where recharge cannot compensate for the evaporation, the lithium in the brine continues to concentrate and enrich, and the longer the evaporation time, the greater lithium enrichment.

The lithium-rich brines in South China are all stored in the pores and fissures of sandstone and mudstone accompanying the rock salts, and the paleoclimate at that time was presumed to be arid based on rock-salt inclusions and sporadic pollen (Li HN et al. 2015). Therefore, an arid to extremely arid climate plays an important role in the formation of lithium-rich brines, both in terms of plateau saline lake-type lithium brine deposits and deep underground brine-type lithium deposits.

4.3. Sources of lithium

Lithium in terrestrial brines comes from a variety of sources. A comprehensive analysis of the geological characteristics of these brine deposits suggests that the surrounding rocks of the brines in the basin contain high lithium concentration, which may provide abundant lithium supply to the water body within the basin under internal and external geological processes.

Various lithium-rich rocks are important sources of lithium in brine. For example, the Li concentration of rhyolite glass in the Macusani region of Bolivia, South America, is as high as 3400×10^{-6} (Wt.). Lacustrine sediments of the Late Miocene to Pliocene tuffs in Clayton Valley, North America, contain as much as 1300×10^{-6} (Wt.) of Li, with an average of 100×10^{-6} (Kunasz IA, 1974). Hofstrta AH et al. (2013) studied siliceous melt inclusions in siliciclastic volcanic rocks in the western United States and concluded that these melt inclusions provided evidence of lithium enrichment prior to extreme eruptions and depletion after eruptions, which is important for determining the origin of lithium-rich brines.

Rivers or hot springs with anomalous-level lithium can carry lithium into lake basins. The lithium concentration of boiling water ejected from the Gulu hot spring in Nagqu, Tibet is 10.4 mg/L, and that of boiling water from Yangbajain is 8.5 mg/L, which is one to several orders of magnitude higher than the usual river and lake water (Mou BL, 1999), suggesting that lithium-rich geothermal fluids in the deep of the earth can be carried to the upper crust and ultimately recharged to the lake through the river drainage. Yu JJ et al. (2013) suggested that the lithium deposit in brines of salt lakes such as Yiliping in the Qaidam Basin is formed by evaporation and concentration of lithium-rich river recharged to the salt lake, and the average lithium concentration of the river water is 0.4 mg/L. The upper part of the river is replenished by warm springs rising along faults in the geothermal field.

The water-rock interaction between surface low temperature water and underground high-temperature fluid with rocks plays a crucial role in the initiation, migration, and storage of lithium. Large amounts of lithium can be released into fluids from rocks. Davis JR et al. (1986) argued that Tertiary volcanism can provide heat and reactive materials for water-rock interactions. They also stated that condensed volcanic glass is widely developed in tuffaceous sandstones and shales. When unstable materials such as volcanic glass is prone to water-rock interactions, fluids with anomalously high lithium concentrations (up to 120×10^{-6}) are formed. Therefore, it is believed that volcanic rocks and other rocks since the Tertiary have provided an important source of lithium for brines through water-rock reactions. Araoka D et

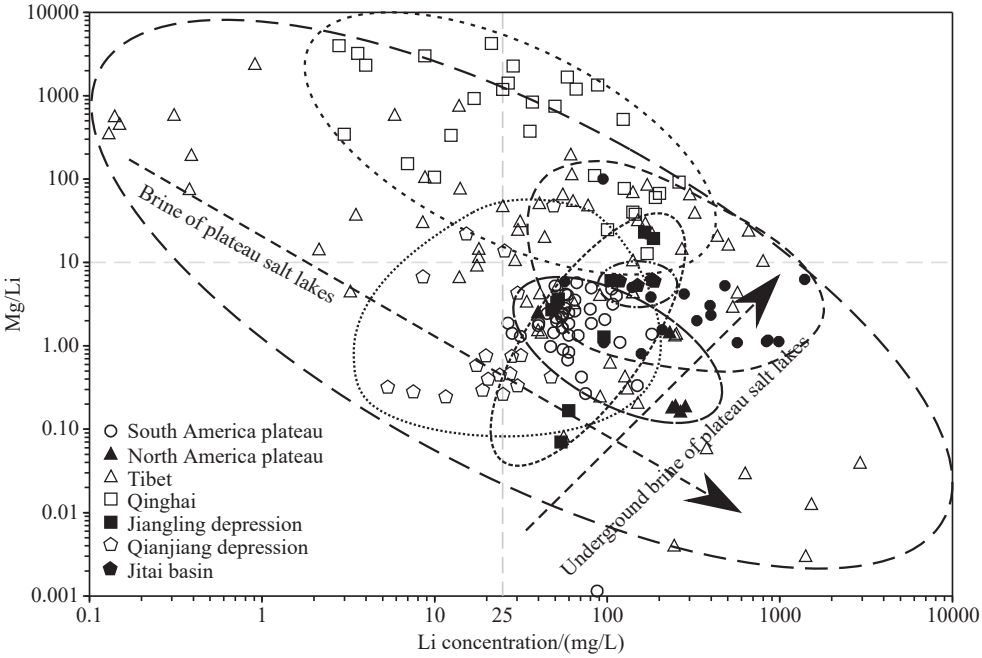

Fig. 14. Relationship between Mg/Li ratio and lithium concentration in terrestrial water body worldwide (data after Chan LH et al., 1993; Huh Y et al., 1998; James RH and Palmer MR, 2000; Kasemann SA et al., 2004; Teng FZ et al., 2004; Tomascak PB, 2004; Kay SM et al., 1994; Munk LA and Chamberlain CP, 2011; Misra S and Froelich PN, 2012; Wang LC et al., 2017; Godfrey LV et al., 2019; Garcia MG et al., 2020; He MY et al., 2020; Weynell et al., 2021, Yu XC et al., 2022; Yan K et al., 2022; Li ZY et al., 2024).

al. (2014) investigated the lithium and strontium isotopes of brines in the Clayton Valley and concluded that lithium may have two possible sources, either from prolonged chemical weathering of the surrounding rocks, providing lithium to the surface water, or from hydrothermal activity between various fluids and the surrounding volcanic rocks. The formation of lithium-rich brines in the Puna Salt Lake in Argentina is associated with the contribution of hot water and weathering of lithium-bearing rocks (Lopez-Steinmetz RL et al., 2018).

By comparing the correlation between Mg/Li ratios and lithium concentrations in terrestrial brines worldwide (Fig. 14), it is found that the Mg/Li ratios in the brines of the South American Plateau, the North American Plateau and the Qinghai-Tibet Plateau are significantly negatively correlated with Li concentration, while the ratios are significantly positively correlated with the concentrations of brines of the Jiangling depression and Qianjiang depression in the Jianghan Basin and the Jitai Basin in South China. It shows that lithium is continuously enriched in the brines of plateau salt lakes during evaporation, while the variating ranges of magnesium are smaller than that of lithium. In addition to the continuous enrichment of lithium, Mg concentration in underground brines in South China has increased significantly, which suggests that the chemical composition of brines is affected by water-rock interaction.

This paper collected data on lithium isotopes, lithium content in surrounding rocks of brines, lithium concentration in most terrestrial brines, rivers, and hot and cold springs that supply brines worldwide. The correlation between δ^7Li and Li content of the surrounding rocks of salt lakes (or concentration in the brines) was analyzed based on this data (Fig. 15). The lithium content of the surrounding rocks of salt lakes in South America, North America, and the Qinghai-Tibet Plateau are generally high, with some reaching 1000×10^{-6} (Wt.). δ^7Li values are also low and below 13‰ (Fig. 15a). The concentration of lithium in rivers and hot and cold springs is mostly below 10mg/L, some values approaching 110mg/L. The δ^7Li values in the water bodies of the South American Plateau and Tibet Plateau are below 17‰, while the variation range of δ^7Li in the Qaidam Basin is wide, ranging from 4‰ to 40‰. This reflects the strong fractionation of lithium isotopes in the rivers and hot and cold springs in the Qaidam Basin. The δ^7Li values are more influenced by atmospheric precipitation or other geochemical processes (Fig. 15b). In addition to generally high lithium concentration of brine worldwide, the relationship between δ^7Li and Li concentration is similar to that of rivers, hot and cold springs that feed brine (Fig. 15c). In other words, the low δ^7Li of brines of salt lakes in South America, North America and the Tibet plateau reflects that the brines of three plateaus have similar provenances or geological processes. The formation of brine lithium deposits is more affected by the interaction of water and rock at higher temperature, and the degree of lithium isotope fractionation decreases under high temperature conditions. Meanwhile, the large variation ranges of δ^7Li in the Qaidam Basin in Qinghai Province, the Jianghan and Jitai basins in South China suggest that the brines of Qaidam, Jianghan and Jitai Basins have undergone different geochemical processes. In general, it reflects the contribution of surrounding rocks around the basin to the lithium of the brine. So, low temperature weathering and high temperature water-rock interaction are important mechanisms for the release of lithium from rocks. Additionally, river and spring water serve as significant carriers for the migration of

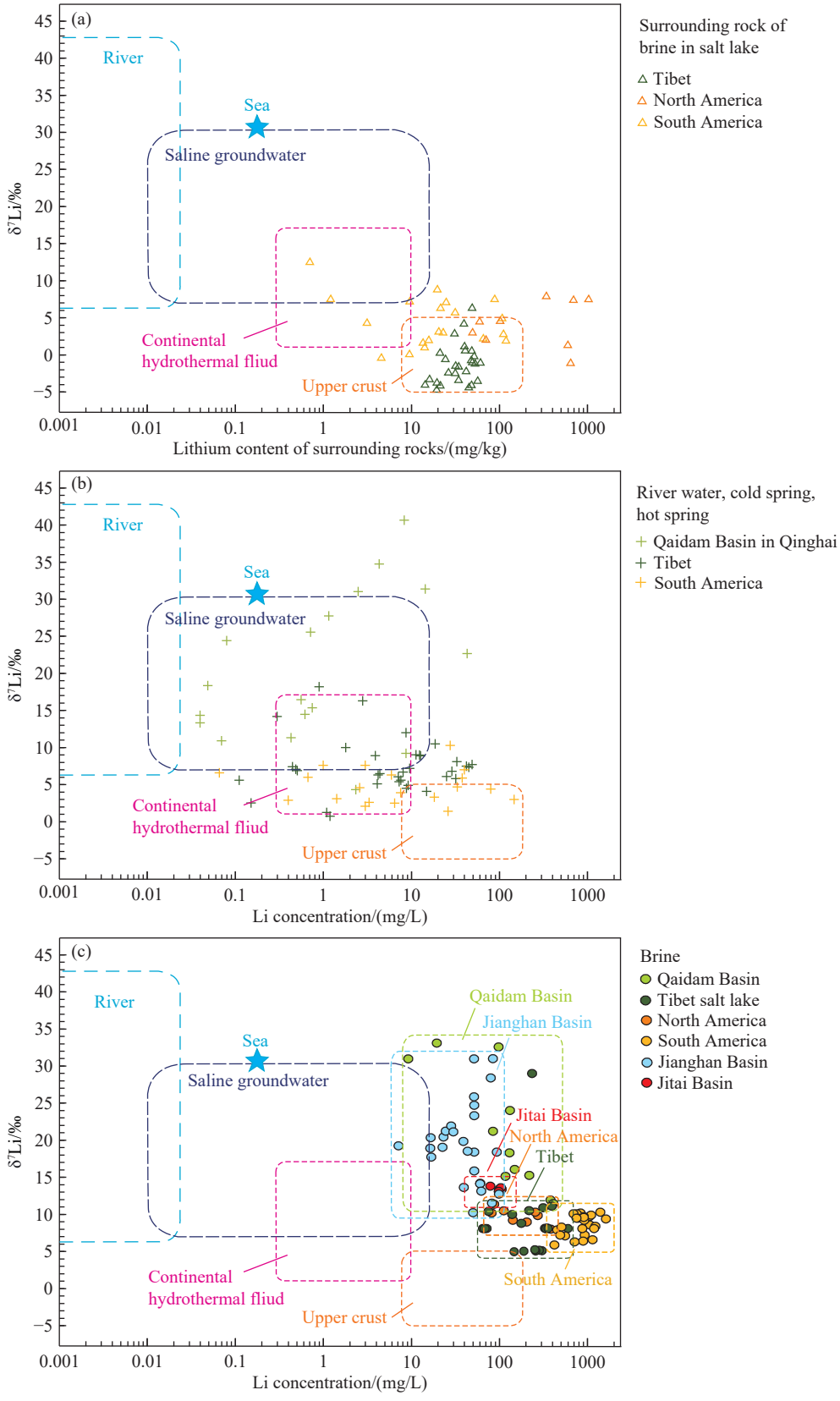

Fig. 15. δ^7Li *vs.* Li concentration or content diagram of terrestrial brines. (a) δ^7Li vs. Li content of surrounding rocks of salt lake brine; (b) δ^7Li vs. Li concentration of river, cold and hot spring; (c) δ^7Li vs. Li concentration of brines. Data for Qaidam basin from He MY et al., 2020; Data for Tibet from Weynell M et al., 2021, Li ZY et al., 2024; North American data cited from Munk LA and Chamberlain CP, 2011; South American plateau salt lake data from Kasemann SA et al., 2004; Kay SM et al., 1994; Godfrey LV et al., 2019; García MG et al., 2020; Data of Jianghan Basin cited from Wang LC et al., 2017; Yan K et al., 2022; The Jitai Basin is from Yu XC et al., 2022. (Worldwide data on rivers, subsurface brines, continental hydrothermal fluids, and continental crust from Huh Y et al., 1998; James RH and Palmer MR, 2000; Chan LH et al., 1993; Tomascak PB, 2004; Misra S and Froelich PN, 2012; Teng FZ et al., 2004).

lithium.

5. Metallogenic regularity of brine lithium deposits

5.1. Metallogenic model of brine lithium deposit

Munk LA and Chamberlain CP (2011) concluded that the genesis of lithium-rich brines in Clayton, Nevada was caused by (1) lithium leaching from lithium-rich rhyolites, (2) pooling and evaporative concentration in a dry saline lake, and (3) evolution of the brines through mixing and water-rock interaction in the subsurface. Hofstra AH et al. (2013) summarized and proposed a model for the formation of lithium brines and lithium-rich clays in the Clayton Valley, U.S., and lithium was filtered into the salt lake through evaporation and concentrated to form lithium brine deposits. Bradley D et al. (2013) have also proposed a preliminary model for lithium brine. They suggest that certain conditions must be met for lithium brine deposits to form. These include: (1) an arid climate, (2) the closed basins for the forming of dry saline lakes, (3) tectonic faults, (4) associated igneous or geothermal activity, (5) suitable lithium source rocks, (6) one or more aquifers, and (7) sufficient time for evaporation and concentration. Lithium brine mineralization is primarily due to evaporation and the interaction between thermal fluids and aquifers. Godfrey LV et al. (2013) suggested that climate has an important influence on lithium enrichment in saline lakes. Specifically, the arid effect of the high altitude of the Central Andes has led to rapid enrichment of lithium brine. Munk LA et al. (2016) summarized the characteristics of lithium brine mineralization in eighteen saline lakes worldwide and concluded that the factors controlling brine lithium mineralization include (1) arid climate, (2) closed basins containing saline lakes, (3) igneous or geothermal activity, (4) tectonically controlled subsidence, (5) source of lithium material, and (6) the need for ample time to concentrate the brine.

5.2. Brine lithium mineralization in salt lakes

Brine-type lithium deposits in salt lakes are primarily distributed over plate subduction zones. The sub-basin tectonics formed under the control of the regional plate movement mechanism provide conditions for the surface runoff transport of lithium-containing fluids to converge, while also undergoing tectonic subsidence and part of the fracture closure in the interior and margins of the basin (Jordan TE et al., 2002), which plays a very important role in storing and preventing the leakage of lithium-bearing brine. The activities of warm and hot springs brought lithium recharge to the salt lakes, and the evaporation effect formed lithium-rich brines.

Liu CL et al. (2021) outlined that ocean-continental plates subduction and continental-continental plates collision led to brine-type lithium mineralization in salt lakes (Fig. 16). The orogenic effect formed plateau landforms and inter mountain basins, which in turn triggered an arid climate. South China block is located in the western Pacific tectonic belt, due to the subduction of the ancient Pacific plate and the formation of coastal mountain ranges. This resulted in the Cretaceous-Palaeogene arid climate in South China, which when coupled with igneous activities transporting a large number of lithium-

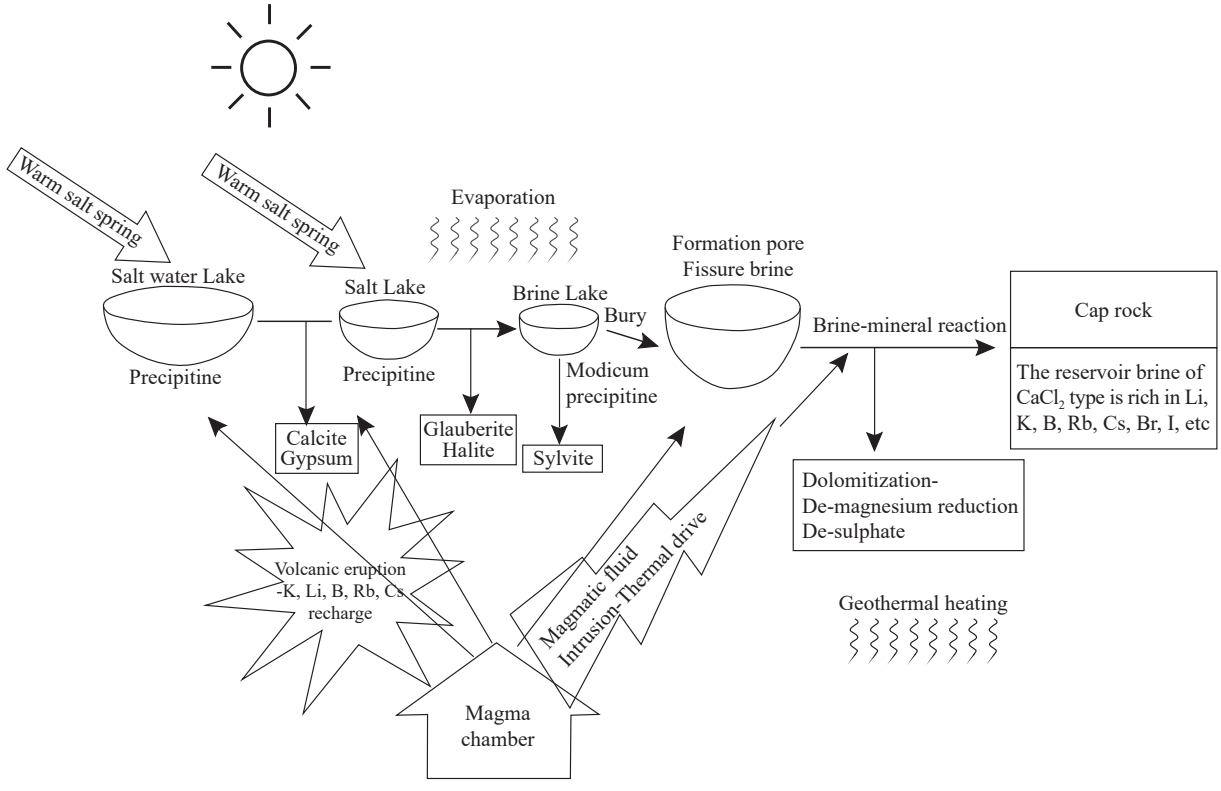

Fig. 16. Genesis of high temperature Li-enriched brine in Jiangling depression, South China (after Liu CL et al., 2013).

forming materials, may have contributed to the enrichment of lithium in brine. Lithium in brine may originate from the weathering of lithium-rich granite and other rocks around the basins or from the leaching of the water-rock interaction of basalt and other rocks at certain depth. Controlled by the extremely arid climate of South China during the Cenozoic, lithium may have been further enriched in the later burial process, forming lithium-rich brine deposits in favorable reservoirs.

The formation process of lithium brine deposits is summarized as follows: oceanic-continental subduction and continental-continental collision caused magma fluid to invade upward, forming lithium-rich geological bodies such as granite, rhyolite and basalt in plateau areas or basins. When underground anomalous geothermal fluid passes through these lithium-rich rocks, through water-rock interaction, the

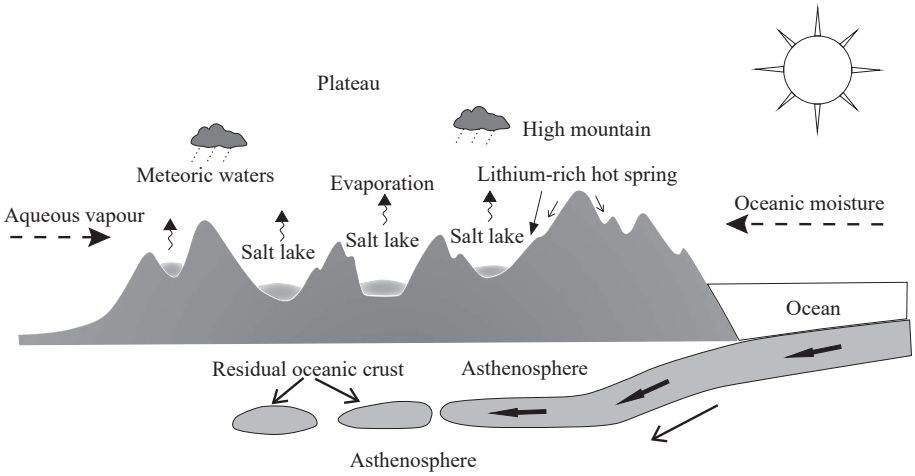

Fig. 17. Kinetic models of the formation of brine-Li deposits in salt lakes of plateaus in the world (after Liu CL et al., 2021).

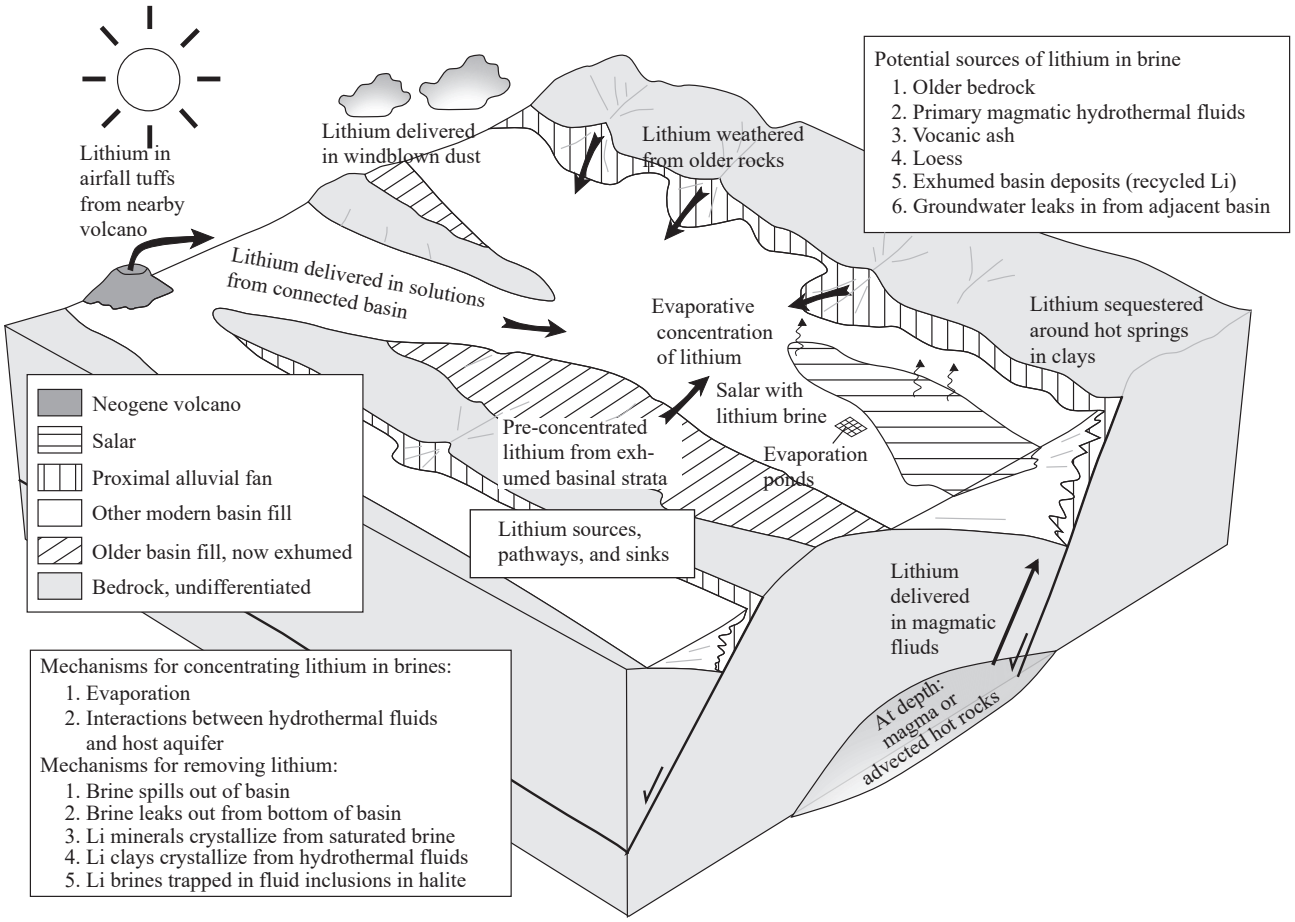

Fig. 18. Summary diagram of the geologic, geochemical, and hyprogeologic features of lithium brines emphasizing the sources, transport, and fate of lithium (after Bradley D et al., 2013).

fluid leaches lithium from some of the rocks at some depth, high heat and high pressure, or topographic elevation caused by the gravitational potential energy driven by the convergence of the secondary basin ridge tectonics or the low-lying areas of the faulted (sunken) basin. The high elevation of plateaus block the entry of water vapor and causes the rain shadow effect, resulting in an extremely arid climate, with higher evaporation than precipitation (Fig. 17). Additionally, source rocks weathering and leaching, as well as the participation of external fluids in the exchange of evaporates dissolution, and clay and other minerals adsorption maintain the dynamic stability of the brine. Under the same conditions, Li in the brine inevitably becomes further concentrated and enriched. As the brine becomes more concentrated, large amounts of gypsum, glauberite, halite, and other salt minerals reach saturation, leading to crystallization and precipitation. The general metallogenic model is shown in Fig. 18 (Bradley D et al., 2013). Lithium is ultimately enriched in salt inter-crystal pores or terminal brines, such plateau-type brine lithium deposits are formed relevantly. When brine is buried by later deposition, the diagenesis effect transforms into ancient salt lake deposits through the dissolution of salt, releasing a large amount of Li into the brine. Thus, brines are stored in the cracks, pores, or other changes reservoir bodies, and form underground brine-type lithium deposits, for example, the deposits in the Jianghan and the Jitai Basins. Localized deep underground thermal fluid can include a large amount of lithium and, at the same time, can accelerate the extraction of lithium from the surrounding rocks, increase the lithium concentrations, and cause the formation of Salton Sea' s high thermal anomaly brine.

6. Conclusions

(i) The terrestrial lithium brine deposits worldwide primarily occur in plateau salt lakes, underground brine (oil field brine), and geothermal springs; the former two types are primarily exploited. Lithium brine deposits in salt lakes are primarily distributed in the Andean Plateau in South America, the Western Plateau of North America, and the Qinghai-Tibet Plateau in China. The LiCl resources are approximately 20.76 Mt, 2.3 Mt, and 23.3 Mt, respectively. Underground brine lithium deposits are primarily distributed in the Jiangling and Qianjiang depressions of Jianghan Basin in South China (lithium resources 5.21 Mt) and Russia's Siberian Plateau, and so on.

(ii) The mineralization of terrestrial brine-type lithium deposits is controlled by tectonic, provenance and arid climate. Brine-type lithium mineralization in salt lakes occurs under specific conditions. The world's three major plateaus have been formed by oceanic-continental plate subduction and/or continental-continental collision, which results in the high landforms of plateaus blocking the oceanic air currents from reaching the interiors of the plateaus. This formation creates an arid climate in the interiors of the plateaus, where the amount of evaporation is far greater than the amount of precipitation, allowing the development of numerous salt lakes. Additionally, plate subduction and collision, along with by magma intrusion, volcanic eruption, activities of hot springs, and other hydrothermal liquids, have caused a large amount of lithium and other mineralized substances into the salt lake. After continuous evaporation, lithium is continuously enriched and mineralized in brines of salt lakes.

(iii) The Mg/Li ratios are negatively correlated with the concentrations of lithium in the brine of the plateau salt lakes, however positively correlated with the concentrations of lithium in the underground brine, indicating that the two types of terrestrial brines have undergone different geochemical evolution processes. Surrounding rocks, rivers, springs, etc., are the main sources of lithium in brines, and water-rock interaction is an important mechanism of lithium released from rocks, which can be answered from the relationship between lithium isotopes and lithium concentrations (or contents) in South America, North America, Qinghai-Tibet Plateau and South China.

(iv) The conditions and processes of underground brine lithium mineralization are that after the ancient salt lake brine, water-rock interaction occurs between the brine and the lithium-rich surrounding rocks, and more lithium is dissolved into the fluid, while the rift environment or the high thermal anomaly of deep magma can further accelerate the water-rock interaction, and with the dissolution and release of lithium by buried salt, lithium deposits are formed in the deep brine of favorable reservoirs.

(v) Brine lithium deposits in Plateau salt lakes are large in reserve scale and high in Li grade, and are currently the main objects of lithium resource exploration and mining utilization. With the successive discoveries of underground brine-type lithium deposits, this type of lithium deposit has attracted more attention, and its further study has important theoretical and practical significance. The plateau and underground types of brine lithium deposits have different deposit genesis and mineralization mechanisms, and their exploratory activities should be emphasized in the future.

CRediT authorship contribution statement

Cheng-lin Liu and Dian-he Liu conceived of the presented idea. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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Supplementary dataset

Supplementary data (Tables. 1–6) to this article can be found online at doi: 10.31035/cg20230128.

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