



## Original Article

## Types, genesis, characteristics and related topics of lithium ore deposits around the world

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### Abstract

The geochemical properties of lithium determine the fact that lithium deposits appear in concentrated belts on the earth, are severely unevenly distributed, and have a variety of types. Lithium deposits include both solid endogenous and exogenous deposits, as well as liquid brine deposits. Endogenetic lithium deposits are mainly related to acidic igneous rocks and related magmatic activities, including pegmatite, granite, greisen, volcanic rock and hydrothermal types. The author of this article predicts that in addition to the above-mentioned lithium deposit types that have been discovered, skarn-type, veinlet-dissemination type, potassium feldspar ± sodium feldspar ± fluorite + quartz vein type, and metamorphic rock-type lithium deposits will be discovered in the near future. Exogenous and sedimentary lithium deposits include carbonate-claystone type, claystone type, salt rock type, coal-related type, and Quaternary evaporation salt type, etc. From the macroscopic perspective of global lithium resources, the liquid brine lithium deposits that occupy the majority of lithium resources include both surface salt lake type and Quaternary evaporation salt type visible to our naked eyes, as well as underground brine type and oilfield water type. Most of the lithium deposits known so far are coexistent and/or associated with other rare metals such as Nb, Be, Ta, Ce, Ga, Sc, Th, U, and rare earth metals. Sometimes Sn and/or B may also appear in lithium deposits. There are very few truly independent lithium deposits.

**Key words:** lithium; ore deposit type; genesis; characteristics

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## 1 Introduction

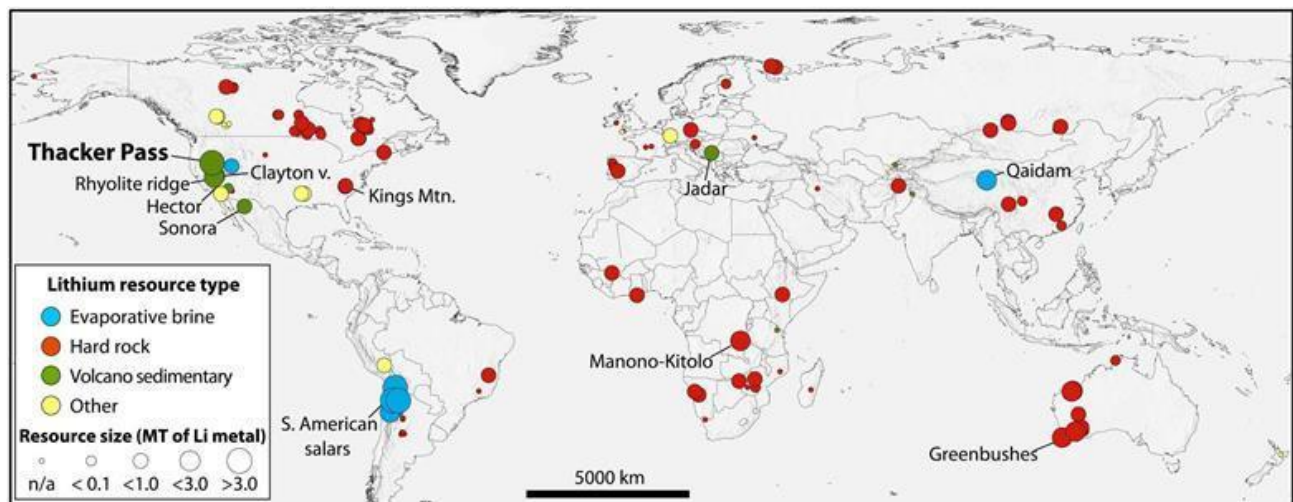
As human environmental protection awareness continues to strengthen, rare metal lithium, the most well-known green energy metal, plays an increasingly important role in our daily lives. At the same time, more and more people are involved in the search, exploration and development of lithium deposits.

In view of this, it is necessary to sort out and summarize the global lithium mineral resources, and on the basis of exploring its geological and geochemical characteristics, classify its deposit types, and then summarize its mineralization laws and origins, so as to find more of this type of energy metals and make greater contributions to improving human life and protecting the earth's environment. This is also the purpose and purpose of this article.

Although scientists have been looking for more efficient other energy metals, lithium metal will remain an indispensable energy metal for a long time in the foreseeable future. Therefore, it is of great significance to classify lithium ore types and explore their origins.

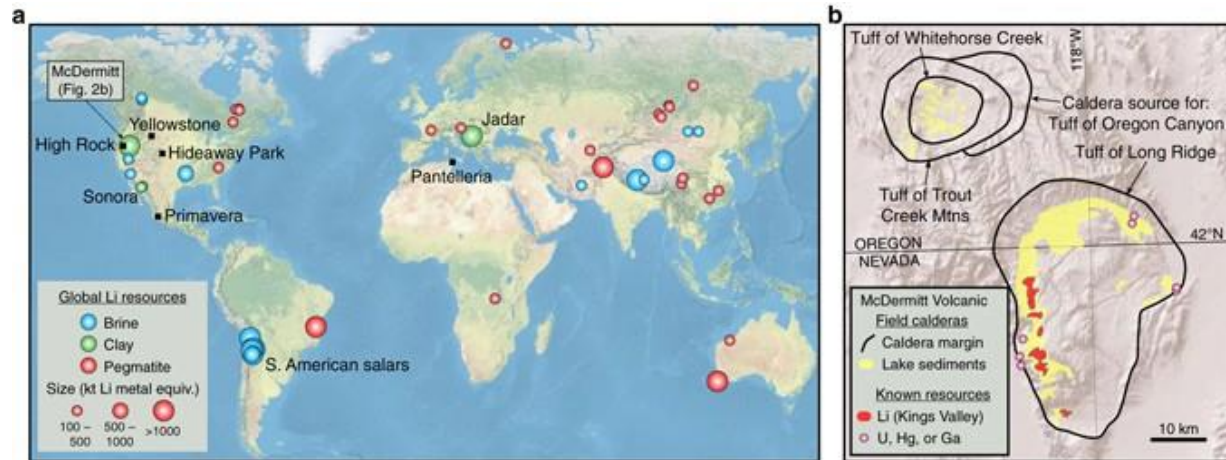
## 2 Ore deposit type

The world's lithium deposits are highly concentrated in South America and North America (73%). Oceania (8%), Asia (7%), Europe (7%), and Africa (5%) have relatively few deposits. These known lithium deposits around the world are distributed in 6 large concentration areas and belong to 23 countries (Figures 1 & 2).



**Figure 1.** Map showing type and relative size of global lithium resources<sup>1</sup>

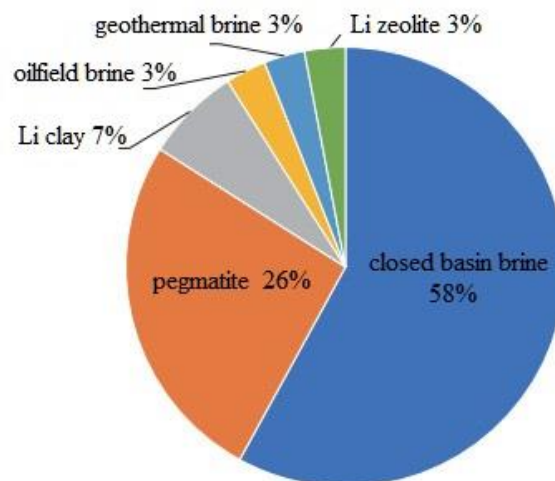
Current production is predominantly spodumene from pegmatites in Australia (47%) and brines underlying salt flats in Chile (30%), China (12%), and Argentina (5%)



**Figure 2.** Location maps of global lithium resources and McDermitt volcanic field

a. Map of worldwide Li brine, clay, and pegmatite resources larger than 100 kt Li and locations of volcanic systems analyzed by Benson et al. (black squares). b. McDermitt Volcanic Field calderas and associated caldera-forming ignimbrites. Also shown are outcrops of caldera lake sediments and locations of the Kings Valley Li deposit and Ga, U, and Hg resources in the McDermitt Caldera<sup>2</sup>

Regarding the classification of global lithium deposit types, geologists in many countries have made various attempts based on their own practices and understandings<sup>3-14</sup>. For example, USGS not only classified lithium deposit types, but also estimated the proportion of each type in that year in 2022 (Figure 3). However, to date, there is no unified classification scheme for lithium deposit types that is universally accepted by the global geological community.



**Figure 3.** Global lithium deposit types and their proportions in 2020<sup>15</sup>

Based on the output status, host rock and genesis of the currently known lithium deposits, especially the developed ones, this paper divides the global lithium deposits into two categories,

several subcategories and many sub-subcategories (Table 1). The two major categories are various liquid brine-type lithium deposits and solid lithium deposits of different genetic types. The main characteristics, representative production areas and deposits of various types of lithium deposits are shown in Table 1, and are briefly described below.

**Table 1.** Global lithium deposit types and their origin

Type	Genetic type	Sub-type	Third level type	Origin/Note
Solid	Endo genetic	Igneous	LCT pegmatite	Australia, Canada, USA, Mexico, China, Zimbabwe, Mali, Congo, Czech, Austria, Germany, Portugal, Sweden
			Granite lithium	Jiangxi, Guangxi & Hunan Provinces, China; Bikita deposit, Zimbabwe
			Greisen	Inner Mongolia, China
			Volcanic	Tecolote in Mexico, Caldera basins in west USA
		Pneumolytic	Cryptoexplosive breccia	China, USA
		hydrothermal	Veinlet-dissemination	Note: Predicted new types to be discovered
			Skarn	
			K/Na-feldspar±fluorite±quartz vein	
		Metamorphic	Metamorphic	
		Liquid	Exo genetic	Sedimentary
Claystone & clay	Yichang, China; Kings Valley, USA; Jadar, Serbia			
Paleosalt rock	China, USA			
Coal associated	China			
Brine	Evaporated salt			Carbonate type: Qinghai-Tibet Plateau, China; Silver Peak, USA; Lithium Triangle, south America
	Oilfield waters			Huatugou chloride oilfield in Qaidam Basin, China; USA
	Salt lake brine			Sulfate type: Qinghai-Tibet Plateau, China
	Underground brine including deep underground well			Halide type: Lithium Triangle, south America
	& geothermal brine			Sichuan & Hubei, China; USA

## 2.1 Liquid ore deposit

The so-called liquid lithium deposit in this article refers to brine lithium deposit. Brine lithium deposit is mainly salt lake brine and intercrystalline brine, which is found in the strata from the Upper Pleistocene to the Holocene. According to its main mineral compositions, brine lithium deposits can be divided into three categories: carbonate type, sulfate type and halide type (Table 1). Among them, the first two are the main objects of salt lake lithium development at present,

especially carbonate brine. Because its magnesium/lithium ratio is very low, it can be directly precipitated from brine, and it is one of the best choices for lithium production at present<sup>3-4, 8-11 & 16-23</sup>.

The generally understood brine lithium deposits refer to the salt lake type lithium deposits that can be mined in South America. It is mainly distributed in Bolivia, Chile and Argentina in South America, which is the so-called "lithium triangle".

Brine-type lithium deposit is an important source of lithium, currently accounting for about 78% of the world's total lithium deposit, and is also the leading direction of future lithium development. Brine lithium deposit generally appears in the following forms, which are subtypes of liquid lithium deposit:

- Oilfield water type
- Evaporated salt type
- Salt lake brine type
- Underground brine type

Fundamentally speaking, there is no substantial difference between the above four forms of brine lithium deposits. In particular, the formation mechanism of underground brine, underground deep well brine and oilfield water type lithium deposits should be exactly the same. The surface salt lake brine visible to our naked eyes should be connected with the other three types of brine deposits in some way, and the source of their minerals will not be essentially different. As for underground brine and underground deep well brine, they are exactly the same in origin, except that underground brine is extracted by digging wells. Therefore, in the classification of this article (Table 1), the type of "underground deep well brine" will not be listed separately, but included in the underground brine type. However, oilfield water brine is still listed separately. After all, this brine is symbiotic with oil and water. Of course, this lithium-containing oilfield water is essentially a type of underground brine, but it is mixed with petroleum. As for the Cenozoic evaporated lithium salt deposits, although they are solid sediments, they have not yet been transformed into rocks. In addition, this kind of salt is essentially derived from brine, so in this classification, it is still classified as brine-type lithium deposit.

### **2.1.1 Oilfield water type**

In the research of liquid lithium deposits in oilfield waters, USGS experts are at the forefront of the world. Half a century ago in the 1970s, USGS geologist Collins noticed that some oilfield waters in the United States contained lithium and conducted sampling and analysis. In 1976, Collins published a professional report entitled *Lithium Abundances in Oilfield Waters*<sup>23</sup>.

For the specific research content and conclusions, please refer to his relevant report. Due to space limitations, I will not go into details here.

The Huatugou oilfield water lithium deposit, located in the Qaidam Basin in the northwest of Qinghai Province, China, in the northeast of the Qinghai-Tibet Plateau, is a chloride-type oilfield water lithium deposit.

### 2.1.2 Evaporated salt type

As early as the 1980s, USGS geologists Ericksen and Salas studied the evaporate and brine lithium deposits in the Salas Salt Lake in the central Andes, and summarized or estimated their geological conditions of formation and resource quantities<sup>22</sup>.

Through their research, they came to the following conclusion: This super-large lithium-boron deposit located in the "Lithium Triangle" of South America, which spans Argentina, Chile and Bolivia, is not only located in a sedimentary basin formed by volcanic activity and faulting, but also the ore-forming materials lithium and boron in the brine and evaporate of the salt lake are derived from volcanic rocks formed by multiple local volcanic eruptions.

### 2.1.3 Salt lake brine type

Since the 1980s, humans have begun to develop and utilize the huge lithium resources in salt lake brines. To date, lithium extraction from brine has become the dominant and backbone of the world's lithium mining industry<sup>8-11 & 16-23</sup>.

Typical salt lake lithium deposits include Uyuni Salt Lake in Bolivia, Salar de Atacama in Chile, Cauchari-Olaroz in Argentina, and Qarhan Salt Lake and Zabuye Salt Lake in China.

In 1995, lithium extracted from brine accounted for only 26% of the world's total lithium production capacity. By 2003, this figure had risen to 91.2%. It is believed that with the continuous advancement of brine lithium extraction technology, the output of brine-type lithium will continue to increase.

Salt lake brine lithium resources are very rich, but because their formation is controlled by climate conditions, geological structure, volcanic activity and mineralization sources, their distribution around the world is extremely uneven. The world's seven most famous salt lake brine lithium deposits are all located in the above-mentioned South American "lithium triangle". A brief description is as follows<sup>3-4, 8-11 & 16-23</sup>:

- Uyuni Salt Lake lithium deposit in Potosi Province, Bolivia: The salt lake brine area is 10,582 km<sup>2</sup>, the average depth of the salt layer is 121 m, the proven lithium reserves are 5.5 million tons, the Li<sub>2</sub>O resources are about 18 million tons, and the lithium concentration of the brine is  $(80-1,150) \times 10^{-6}$ .
- Atacama Salt Lake lithium deposit in Antofagasta Province, Chile: The salt lake brine area is 2,229 km<sup>2</sup>, the salt layer depth is 360-400 m, the Li<sub>2</sub>O resource is approximately 5.3 million tons, and the brine lithium concentration is  $(1,000-4,000) \times 10^{-6}$ .
- Litio Salt Lake lithium deposit in Antofagasta Province, Chile: The salt lake resources are 3.2 billion m<sup>3</sup>, containing 502,000 tons of lithium and a lithium grade of 0.157%.
- Nx-Uno Salt Lake lithium deposit in Antofagasta Province, Chile: The estimated salt lake resources are 1.4 million tons.
- Hombre Muerto Salt Lake lithium deposit in Salta Province, Argentina: The salt lake brine area is 565 km<sup>2</sup>, with an estimated lithium brine content of 800 billion tons, Li<sub>2</sub>O resources of approximately 850,000 tons, and brine lithium concentration of  $(220-1,000) \times 10^{-6}$ .



- Cauchari-Olaroz Salt Lake lithium deposit in Jujuy Province, Argentina: The total resources of the salt lake are 4.575 billion m<sup>3</sup>, containing 2.7402 million tons of lithium and a lithium grade of 0.06%. The reserves are 7.710 billion m<sup>3</sup>, containing 517,100 tons of lithium and a lithium grade of 0.067%.
- Vida Salt Lake lithium deposit in Catamarca Province, Argentina: Salt Lake Li<sub>2</sub>O resources 1.573 million tons, Li<sub>2</sub>O reserves 214,000 tons.

China's brine lithium deposits are mainly distributed in the salt lakes of the Qinghai-Tibet Plateau. There are three types of brine: carbonate, sulfate and chloride. Currently, carbonate and sulfate types are mainly developed. China's unique high-quality carbonate lithium deposits are concentrated in the central part of Qiangtang, Tibet, that is, the central and northern part of the Gangdise Plateau, and the south side of the Nagqu-Shiquanhe Highway. Sulfate lithium resources are mainly distributed in the Qaidam Basin and the north side of the northern Tibet lithium resource belt. Chloride salt lake lithium deposits are distributed in the uninhabited areas of northern Tibet and the Hoh Xil area of Qinghai. The country's representative brine lithium deposits include:

- Qinghai Chaerhan Salt Lake lithium deposits: including 5 super-large deposits (lake salt, magnesium salt, boron, lithium, rubidium) and 3 large deposits.
- Tibet Zabuye Salt Lake lithium deposit: Li<sub>2</sub>CO<sub>3</sub> resources of 1.83 million tons.

In order to make full use of the local natural resource advantages and vigorously develop the domestic economy, in 2016, Chile listed 15 potential salt flats for "bidding" worldwide, one of which was the Pujsa Salt Lake. Relevant data show that the lithium concentration of the salt lake brine is 220-620 mg/L.

Similarly, in September of the same year, the mining and environmental department of Catamarca Province, Argentina approved Neo Lithium's environmental report and exploration plan for the Tres Quebradas (3Q) project. This means that these mining companies have officially entered the exploration stage of brine lithium deposits, and can build and operate test evaporation pools for brine lithium deposits, as well as necessary laboratories, permanent and semi-permanent work camps and other related facilities.

#### **2.1.4 Underground brine type**

In recent years, the world has continuously strengthened the exploration and prospecting of underground brine lithium deposits, and has achieved remarkable results. Among them, the United States has attracted the most attention from the world. Nevada in the country has become a hot spot for prospecting underground brine lithium deposits.

As early as 1977, USGS carried out relevant exploration in Nevada. One of the boreholes numbered CV-5 with a footage of 146 m obtained underground brine containing  $24 \times 10^{-6}$  -  $110 \times 10^{-6}$  lithium.

On December 21, 2016, Advantage Lithium Corp. announced that the company had drilled lithium-rich hot brine in the Clayton Valley area of Nevada. Among them, the lithium content in

the range of 209.23-596.92 m was 243.66 mg/L, which was much higher than the lithium content in the brine drilled by USGS in 1977.

## 2.2 Solid ore deposit

The types of solid lithium deposits known in the world are more numerous and more complex than the brine lithium deposits mentioned above (Table 1, Figures 1-4). Similar to the brine lithium deposits mentioned above, many geologists around the world have divided the types of solid lithium deposits into different categories based on their understanding of lithium deposits and practical experience<sup>3-4 & 7-15</sup>.

Based on his own practical experience and referring to the opinions of predecessors, the author of this article divides solid lithium deposits into the following types and subtypes (Table 1).

Similar to liquid lithium deposit, solid lithium deposit is also widely found on all continents around the world, but its distribution is also uneven, and there are also local clusters of output and concentrated belts (Figures 1-4). There are also many such lithium deposits in China.

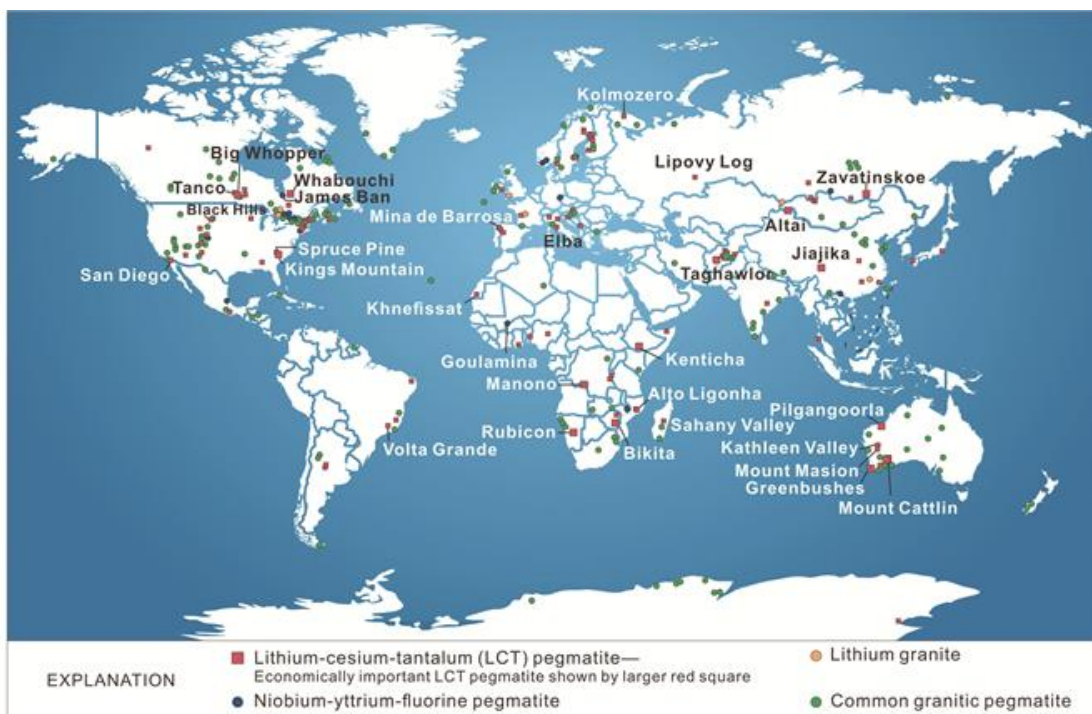


Figure 4. Distribution map of the world's major LCT pegmatite lithium deposits<sup>5</sup>

Solid lithium deposit includes both endogenous deposits such as pegmatite, granite, pneumatolytic hydrothermal and/or cryptoexplosive breccia, and exogenous sedimentary rock types such as carbonate-claystone, mudstone or claystone, and coal-associated type (Table 1). Each is briefly discussed below.

### 2.2.1 Pegmatite type

In a sense, pegmatite-type lithium deposits are the main and possibly the only solid lithium deposits that can be developed and utilized at this stage. This type of deposit is widely distributed, mainly in relatively stable geological units such as ancient crystalline shields and platforms, or in non-orogenic environments of tectonic domes and accretionary continental margins (Figures 1-4)<sup>4, 7, 10-13, 15 & 24-33</sup>. Chen et al. concluded that the LCT pegmatite-type lithium deposits in the southern hemisphere were mainly formed in the Precambrian, followed by the Early Paleozoic<sup>25</sup>. The pegmatite-type lithium deposits in Eurasia and North America in the northern hemisphere were mainly formed in the Late Paleozoic and later, and relatively few were formed in the Precambrian. China's pegmatite-type lithium deposits are mostly found in geosyncline fold belts and transition zones between uplifts and depressions within platforms. The rocks related to the deposits are mainly Hercynian and Yanshanian granites.

The lithium-containing minerals of pegmatite, especially metasomatic pegmatite-type lithium deposit, are mainly spodumene, lepidolite, petalite, lepidolite and ferrolithium mica. This type of deposit has a high grade and is relatively easy to mine. Lepidolite, on the other hand, is mainly produced in granite-type lithium deposit<sup>10-13</sup>.

Some researchers divide pegmatite-type lithium deposits into banded pegmatite-type lithium deposit and non-banded pegmatite-type lithium deposit according to whether it is zoned. The mineral composition of the banded pegmatite-type lithium deposit is complex. In addition to containing a large amount of spodumene, petalite, lepidolite, eucryptite and lepidolite, it also often contains a small amount of beryl, niobium-tantalite, cassiterite, cesium garnet and other rare metal minerals that can be comprehensively utilized. The spodumene crystals in this type of deposit are coarse and the content is generally around 20%. It is the main source of high-quality low-iron spodumene concentrate. A typical example is the Green bushes lithium deposit in Australia<sup>15 & 24-33</sup>.

Non-zonal pegmatite lithium deposits are usually independent lithium deposits, or lithium deposits with small amounts of beryllium and tantalum. Pegmatite is basically a single-phase homogeneous rock mass, composed of albite, microcline, quartz, muscovite and spodumene, as well as a small amount of beryl, cassiterite and tantalum-niobium minerals. Spodumene is evenly distributed, accounting for 25% of the total rock mass, and is an important source of pegmatite-type spodumene. The Kings Mountain deposit and the Bessemer City deposit in the "cassiterite-spodumene" belt of North Carolina, USA, can be used as typical representatives of this type.

China's spodumene-type lithium deposits are mainly distributed in Xinjiang, Sichuan, Fujian and the eastern Qinling Mountains in Shaanxi, including the Keketuohai and Kelumute lithium-beryllium-niobium-tantalum deposits in Xinjiang; the Jiajika, Kelin and Zawulong lithium-beryllium-niobium-tantalum deposits in Sichuan; and the niobium-tantalum-lithium deposits in Nanping, Fujian. The common feature of this type of deposit is the coexistence and/or association of multiple rare metals. In different historical periods, people would focus on mining certain minerals according to the needs at the time. For example, the rare metal deposits such as



Keketuohai and Kelumute in Xinjiang were mainly mined for beryllium in the early days, but in recent years, they have focused on the development and utilization of lithium<sup>8-14, 16, 18 & 25</sup>.

Unlike brine lithium deposit, which is limited to a few basins and has a large scale of individual deposits, individual pegmatite lithium deposit is small in scale but widely distributed, distributed on all seven continents in the world, with high grade and good ore quality, and relatively mature mining and refining technology. Therefore, it has aroused the interest of exploration all over the world, and the exploration progress has been considerable and fruitful.

For example, the Pilgangoora world-class pegmatite lithium ore field in Western Australia is located in the Archean Pilbara Craton greenstone belt, with the advantages of shallow burial depth, thick ore body and high grade. Data in July 2016 showed that the total lithium resources of the ore field reached 128.6 million tons, with an average  $\text{Li}_2\text{O}$  grade of 1.22%<sup>28</sup>.

Earlier in February 2015, European Metal Holdings announced that the estimated ore resources of the Sinovik deposit it owned were 515 million tons, with an average  $\text{Li}_2\text{O}$  grade of 0.43%, that is, the  $\text{Li}_2\text{O}$  resources were 2.21 million tons, and the lithium carbonate equivalent was 7 million tons. This made the deposit a world-class lithium deposit at the time. Recently, the deposit upgraded its resource volume: its latest ore resource volume is 657 million tons, with a  $\text{Li}_2\text{O}$  grade of 0.43% and a tin grade of 0.04%.

The Taghawlor pegmatite lithium deposit in Uruzgan Province, Afghanistan, has a  $\text{Li}_2\text{O}$  resource of 1.46 million tons and a lithium grade of 0.08%-2.80%<sup>35</sup>.

The pegmatite lithium deposit in Yichun, Jiangxi, China, has a total ore of 150 million tons and a  $\text{Li}_2\text{O}$  resource of 510,400 tons<sup>36</sup>.

Pegmatite is an important source of many rare metals including lithium, such as tantalum, niobium, beryllium, cesium, rubidium, scandium, thorium, uranium and rare earth.

Most of the lithium ores with mining value in solid lithium deposits, such as spodumene, lepidolite, spodumene and phosphate spodumene, are developed in replacement pegmatite veins. Important production areas of this type of lithium deposits include Australia, the United States, Zimbabwe, Canada, Mexico and China. Famous pegmatite lithium deposits include Australia's Green bushes lithium mine, one of the oldest spodumene mines in the world; Australia's Pilgangoora spodumene mine, the United States' Kings Mountain lithium mine, the Manono lithium mine in the Democratic Republic of the Congo (DRC), and the Jiajika lithium-beryllium deposit in Sichuan, China, and the Keketuohai No. 3 mine in Xinjiang. All lithium mines currently in production in Australia are spodumene mines<sup>4, 7, 10-13, 15 & 24-36</sup>.

In recent years, the newly discovered or increased reserves of pegmatite lithium deposits mainly include Manono in the Democratic Republic of Congo, Manono-Kitolo in the Democratic Republic of Congo, Goulamina in Mali; Pilgangoora, King Col, Kathleen Valley, Buldani, Grant, Bald Hill, Youanmi, and Dorchap Dyke Swarm in Australia; Whabouchi, Authier, Tansim, and Seymour Lake in Canada; Carolina Tin-Spodumene Belt in the United States, Zinnwald in Germany, Bergby in Sweden, Alvarre in Portugal, Wolfsberg in Austria; and Jiajika, Lijiagou, Dangba, Yelonggou, Dahongliutan, Tugman and Chakabeishan in China.

China's pegmatite lithium deposits are mainly produced in the Hercynian and Yanshanian granites. The deposits are composed of pegmatite veins that appear in groups and bands, and the veins often have structural zoning characteristics of symmetry and concentric mineral symbiosis. The deposits are mainly lithium-beryllium, with associated niobium-tantalum-rubidium-caesium, etc. The lithium minerals are mainly spodumene, and there are also lithium mica and iron lithium mica. The  $\text{Li}_2\text{O}$  grade of the ore is mostly between 0.8% and 1.4%, and the scale of the deposits is mainly large and medium. It is mainly distributed in Xinjiang, Sichuan, Henan, Hunan and Fujian, China<sup>8-14, 16, 18 & 25</sup>.

Pegmatite-type lithium deposits have certain commonalities, but the differences between pegmatite-type lithium deposits in different regions are also obvious. For example, different pegmatites contain different mineral elements, and their surrounding rock lithology, surface exposure; alteration and zoning development degrees also have different degrees of differences.

Some researchers divide pegmatites into Li-Cs-Ta (LCT), Nb-Y-F (NYF) and mixed LCT+NYF types. Among them, LCT-type pegmatites are characterized by peraluminous, enriched flux components ( $\text{H}_2\text{O}$ , F, P, B) and rare elements (Li, Rb, Cs, Nb, Ta, Be, Sn), and extremely low Nb/Ta ratios (<5). In other words, lithium deposits are mainly produced in pegmatites such as LCT, so many researchers call pegmatite-type lithium deposits LCT pegmatite-type lithium deposits<sup>4, 7, 10-13, 15 & 24-36</sup>. LCT-type pegmatites usually show internal zoning, including boundary zones, wall zones, intermediate zones and core zones. In addition, metasomatism, layered fine-grained rocks, and geodes may also be developed<sup>13</sup>. A good example of an LCT pegmatite-type lithium deposit is the Renli pegmatite-type tantalum-niobium-lithium deposit in Hunan, China.

### 2.2.2 Granite type

Most of the pegmatites in the so-called pegmatite-type lithium deposits mentioned above are granite veins, and their formation is inseparable from granite intrusions. In fact, pegmatite-type lithium deposits do appear spatially around granite intrusions and show certain zoning characteristics. Granite pegmatites have similar mineral and chemical compositions to low-eutectic granites and are usually genetically related to highly differentiated granites<sup>32-33</sup>.

In a sense, granite intrusions and pegmatite veins are of the same origin, and can be said to be from the same mother, but there may be some differences in the time of formation, that is, they are the products of different diagenetic stages. Pegmatite veins are often formed at the end of the diagenetic stage of granite intrusions. Therefore, when the pegmatite veins of the same origin contain minerals, parts of the related granite intrusions, such as marginal phases, also have the probability of mineralization. This should be one of the ways in which the so-called granite-type lithium deposit is formed.

Another type of granite-type lithium deposit is similar to the well-known porphyry copper deposit, that is, the lithium mineralization in granite appears in the form of veinlet-dissemination.

The large-scale Jiajika lithium deposit in Kangding, Sichuan Province, China is a fine-grained alkaline granite-type lithium deposit rich in spodumene<sup>37</sup>. The Yichun Li-Nb-Ta deposit in Jiangxi Province, China, is formed in fine-grained lepidolite albite granite and muscovite albite granite of the early Yanshan orogeny and consists of three ore sections. The deposit is mainly

primary tantalum and niobium ore, accounting for about 99.2% of the total reserves. Ore minerals include lepidolite, tantalite-columbite, tantalum-niobium-rich rutile, cassiterite and wolframite, etc. The alteration of the surrounding rocks includes albite, lepidolite, and greisen. Among the proven reserves, tantalum, lithium, rubidium and cesium are all at super-large scales, and niobium is at large scale. The mineralization type is the so-called highly fractionated granite-type lithium deposit<sup>35</sup>.

### 2.2.3 Pneumatolytic hydrothermal (cryptoexplosive breccia) type

The Weilastuo tin-lithium polymetallic deposit in Inner Mongolia, China, combines a variety of mineralization types: granite-type Rb ore, granite-type Sn-Zn ore, quartz vein-type Sn-Zn ore, sulfide vein-type Cu-Zn-Pb-Ag ore, and cryptoexplosive breccia-type lithium ore<sup>38</sup>.

In the early days, the deposit mainly mined sulfide and quartz vein-type Sn, Cu, and Zn deposits. In 2017, a cryptoexplosive breccia pipe was found in the deep part of the mining area, which contained granite-type Sn and Rb ore bodies. After further analysis and research, it was found that the cryptoexplosive breccia pipe was enriched with lithium, which is a typical example of a cryptoexplosive breccia-type lithium deposit.

The cryptoexplosive breccia pipe is generally columnar with thin top and thick bottom. It lengthens 247 m, deepens 640 m, and has a vertical height of 480 m. It is inclined in the northwest direction and lies sideways in the south direction, with a side-lying angle of about 76°. The cross section is an ellipse with a long axis strike of nearly 30° and a diameter of 140-300 m. There is a shattered fracture zone at the edge of the cryptoexplosive breccia pipe, and there are shattered breccia zones and cryptoexplosive breccia zones inside. The shattered and cryptoexplosive breccia zones are full-rock mineralized, with lithium and rubidium as the main mineralizing elements, accompanied by niobium, tantalum, beryllium, cesium, tin, tungsten, molybdenum, copper, zinc and other beneficial components. The breccia pipe is strongly altered with greisen, amazonite and fluorite, and lithium mica is widely distributed. The Li<sub>2</sub>O grade is between 0.8% and 3.6%, with an average grade of 1.25%. The Rb<sub>2</sub>O grade is between 0.1% and 0.58%, with an average grade of 0.35%.

The proven amount of lithium ore in the cryptoexplosive breccia pipe is 27.8 million tons, Li<sub>2</sub>O is 357,000 tons, and the grade is 1.28%. Rb<sub>2</sub>O is 94,000 tons, and the grade is 0.34%. It is mainly composed of iron lithium mica and lithium mica.

In terms of the origin, the cryptoexplosive breccia pipe here should be formed by pneumatolytic hydrothermal. Therefore, the deposit is also a kind of hydrothermal mineralization.

### 2.2.4 Greisen type

Some researchers believe that the above-mentioned Verastuo lithium polymetallic deposit is the first large-scale greisen-type lithium deposit discovered in Inner Mongolia, China<sup>38</sup>.

In fact, if it is indeed a greisen-type lithium deposit, it is also the first known case in the world, not just in Inner Mongolia Autonomous Region or the whole of China. This point will not be discussed here.



In addition, even if it is a greisen-type lithium deposit, there is no contradiction with the above-mentioned name of it as a cryptoexplosive breccia-type lithium deposit: from the mineral and chemical composition of the ore-bearing rock, it is greisen. Strictly speaking, this so-called greisen should be a kind of altered granite, that is, a granite-type lithium deposit. But from the perspective of ore structure, this is also a relatively typical cryptoexplosive breccia-type lithium deposit.

Therefore, both classifications make sense. Of course, they can be combined and called magmatic hydrothermal cryptoexplosive greisen breccia lithium polymetallic deposit.

### **2.2.5 Volcanic rock type**

On January 6, 2016, Canadian Alix Resources announced that it had discovered a lithium-rich clay layer in Tecolote, Mexico, with an estimated resource of 43.3 million tons and an average lithium grade of 0.3005%. Tecolote lithium mineralization is developed in rhyolitic tuff, welded tuff and volcanic breccia from the Paleogene-Neogene Oligocene to Miocene, and the ore body is composed of a series of lithium-containing clay layers.

Of course, from the final result, this type can also be regarded as a clay-type lithium ore. But in essence, this is a volcanic rock type lithium mineralization.

Benson et al. (2017) demonstrated that lake sediments preserved within intercontinental rhyolitic calderas formed on eruption and weathering of lithium-enriched magmas have the potential to host large lithium clay deposits. They compared lithium concentrations of magmas formed in a variety of tectonic settings using in situ trace-element measurements of quartz-hosted melt inclusions to demonstrate that moderate to extreme lithium enrichment occurs in magmas that incorporate felsic continental crust. Cenozoic calderas in western North America and in other intercontinental settings that generated such magmas are promising new targets for lithium exploration because lithium leached from the eruptive products by meteoric and hydrothermal fluids becomes concentrated in clays within caldera lake sediments to potentially economically extractable levels<sup>2</sup>.

From this, we can see that there is a mutual transformation relationship between igneous rock type, sedimentary type, brine type and other kinds of lithium deposits. Even you have me, I have you. In other words, there is no clear division of lithium deposit types, but there is a transition between them, and even a genetic connection. The above two types of volcanic rock type lithium mineralization can also be classified as sedimentary clay rock type. Therefore, some researchers believe that the formation of brine type lithium deposits is closely related to volcanic activity. This point will be discussed in the relevant part later.

### **2.2.6 Sedimentary type**

Because the three major rock types, i.e. igneous, metamorphic rocks and sedimentary rocks, have been circulating and transforming each other through weathering, erosion, temperature and pressure, when a specific mineral is found in one of the rock types, it can be found in other rock types. This is a general rule shared by most minerals, especially metal minerals.

Therefore, since igneous rocks including pegmatite, granite and greisen can produce lithium, metamorphic rocks and sedimentary rocks must also have this mineral. This is indeed the case. Lithium mineralization or associated and symbiotic lithium mineralization has indeed been found in many sedimentary rocks or sedimentary deposits, and some have even reached economic indicators that can be mined.

The ore-bearing rocks of sedimentary lithium deposits are diverse. Among them, there are independent lithium deposits and/or lithium mineralization, as well as associated and/or symbiotic lithium deposits and/or lithium mineralization. For example, some bauxite, coal and kaolin deposits around the world are associated and/or symbiotic with lithium mineralization. However, the lithium content in this type of lithium ore is generally not high, and the occurrence state of lithium is not clear, or lithium is locked in the lattice of clay minerals without its own independent minerals. Most of them are difficult to effectively develop and utilize and have been ignored for a long time, and are considered to be lithium mineralization belts with no independent mining value<sup>4, 10-11, 15, 24 & 39-42</sup>.

Until 2012, a giant lithium deposit was discovered in the Jader Basin in Serbia. The ore mineral is a new mineral Jadarite containing both lithium and boron. The ore body is produced in the Miocene lacustrine sedimentary rocks. The tuff layer, low resistivity, and low gravity anomaly can be used as prospecting signs. According to research, the beneficiation process of the ore in this deposit is relatively simple<sup>4</sup>. From then on, people's understanding of sedimentary lithium deposits was refreshed, and they also realized that sedimentary rock lithium deposits have independent development potential.

According to the host rock type where lithium deposits are located, sedimentary lithium deposits can be divided into the following subcategories:

- **Carbonate-claystone type Li-Ga-REE deposits** : In recent years, Chinese geologist Wen and his team have discovered the abnormal enrichment of Li-Ga-REE in the Carboniferous and Permian claystones in Guizhou and Yunnan. Geological and geochemical studies have shown that these lithium-rich clays are formed by long-term weathering and deposition of underlying carbonate rocks. Various micro-area analysis methods have shown that lithium is enriched and mineralized in large quantities under special physical and chemical conditions at certain stages of clay evolution. This lithium mineralization is obviously different from volcanic rock-type clay lithium ore in terms of genesis and is a new type of lithium deposit. The newly discovered "carbonate clay-type lithium deposit" is located in central Yunnan. The ore body is located in the Daoshitou Formation of the Lower Permian, which is a set of continental margin-coastal sedimentary rock layers. These newly discovered clay-type lithium deposits are all located in carbonate rock formations. Preliminary exploration shows that the lithium-rich ore layer is stably distributed, 2-16 meters thick, with a  $\text{Li}_2\text{O}$  grade of 0.10%-1.02% and an average grade of 0.30%. In the area of 7.2 square kilometers, a total of about 340,000 tons of lithium oxide resources (Class 334 of Chinese standards) have been obtained. It is predicted that the lithium resources in the entire central Yunnan region will exceed 5 million tons.

- **Clay type** : As early as the 1970s, the United States had extracted 75% of the lithium from ancient weathering crust clay rocks. The hectorite clay in the western United States contains a huge amount of lithium resources. The world's well-known clay-type lithium deposits include the Mc Dermitt lithium deposit in King Valley in northern Nevada, the Thacker Pass lithium deposit in the country, the Sonora lithium deposit in the central basin of Mexico, and the Jadar lithium deposit in Serbia. Lithium-rich clays are mainly clays rich in hectorite, saponite and steatite. The newly discovered boron and lithium silicate mineral Jadarite in the Jadar lithium deposit in Serbia makes the mine a rare special mineral in the world that can simultaneously develop two important resources, boron and lithium. The content of  $\text{Li}_2\text{O}$  is as high as 7.3%. The current estimated Jadar lithium ore is 114.6 million tons, with a  $\text{Li}_2\text{O}$  grade of 1.8%, that is, the  $\text{Li}_2\text{O}$  resource can reach 2.06 million tons<sup>41</sup>. The discovery of the new Jadarite mineral and the exploration and development of the Jadar lithium-boron deposit have promoted the search for sedimentary lithium deposits in Eastern Europe and around the world. The upper lithium-bearing minerals of the deposit are mainly hectorite, and the lower lithium-bearing minerals are polysilicon lithium mica.
- **Bauxite type** : The  $\text{Li}_2\text{O}$  content in the Dazhuyuan bauxite in Guizhou, China is greater than 0.50%. Lithium can be mined independently, or lithium and bauxite can be mined simultaneously. As for the bauxite and clay deposits with a  $\text{Li}_2\text{O}$  content greater than 0.05% in the world, lithium can be developed and utilized as a paragenetic/associated mineral. I believe that once relevant technological breakthroughs are achieved in the future, the large-scale development and comprehensive utilization of such minerals will surely flourish.
- **Coal-related associated type**: Clay deposits in the Carboniferous Benxi Formation in the North China coal mining area are widely distributed and are an important refractory raw material base in China. Among them, clay deposits, bauxite deposits and their surrounding clay rocks in Jiaozuo, Henan, Yuncheng, Shanxi and other places generally contain lithium, and the lithium oxide content far exceeds the lithium requirements of a lithium-gallium bauxite deposits in southwest China. The resource volume of such deposits can often reach a super-large scale.
- **Paleosalt rock type**: This type of lithium deposit is formed after the lithium compounds in the ancient brine-type lithium deposits become sedimentary rocks.
- **Lacustrine evaporate type** : Similar to the ancient salt rock type lithium deposit, this type of solid lithium deposit is formed by the accumulation of lithium minerals in the brine of the Quaternary salt lake. However, due to its shorter time than the above-mentioned ancient salt rock type, it has not been baptized by high temperature and high pressure and has not yet formed into sedimentary rock. Strictly speaking, this is a brine type lithium deposit, but considering its material state, it is still placed in the sedimentary type lithium deposit.

The common characteristics of the above-mentioned sedimentary lithium deposits are: the mineralization era is relatively new, generally Cenozoic. The mineralizing materials mainly come from lithium-rich volcanic materials, and a small amount comes from the weathering and erosion of other surrounding solid lithium deposits such as pegmatites and granites. Lithium mainly exists in the form of minerals such as hectorite, hectorite and jadarite. It is generally formed in closed lake sedimentary basins that are conducive to the convergence, concentration, enrichment and deposition of lithium-containing fluids. Most of them have hydrothermal activities and/or brines to help leaching lithium from rocks. In addition, the alteration produced by hydrothermal and/or brine can form clay minerals that adsorb lithium. Sedimentary lithium deposits are characterized by wide coverage, large ore body thickness, and amazing reserves and resources. This type of lithium deposit is mainly produced in the form of alluvial layers, swamp phases, lake phases and their combined phases in clay rocks and/or sedimentary basins.

### 2.2.7 Predicted lithium deposit types

From the above content, it can be seen that there are cross-transition or cross-type relationships between different types of lithium deposits, and sometimes it is difficult to completely define which type they belong to. Such as granite type and greisen type, greisen type, pneumatolytic hydrothermal type and cryptoexplosive breccia type, volcanic rock type and sedimentary rock type, clay rock type and carbonate-clay rock type, etc. There is no clear boundary between liquid brine type and sedimentary lithium deposits. For example, there is no clear boundary between evaporation sedimentary salt type and brine type, because there is a transition relationship between them.

The author of this article has reason to believe that in the near future, the following new types of lithium deposits will be discovered (Table 1):

- **Veinlet-dissemination type** : related to granite (porphyry) magmatic activities and various hydrothermal activities.
- **Skarn type**: related to granite magmatic activities and various hydrothermal activities.
- **Potassium feldspar ± sodium feldspar-fluorite ± quartz vein type** : related to granite magmatic activities, metamorphism, migmatism and/or various hydrothermal activities.
- **Metamorphic rock type** : related to different types of metamorphism, migmatization and related hydrothermal activities.
- **Placer type** : including coastal placer and continental river and lake placer.

### 2.3 Other options for lithium ore classification

According to the primary and secondary positions of lithium in the corresponding mineral deposits, global lithium deposits can also be divided into three categories: independent lithium deposits, symbiotic lithium deposits, and associated lithium deposits.

In fact, whether it is liquid or solid lithium deposit, most of them are symbiotic and/or associated lithium deposits, and there is very little truly independent lithium deposit. For example, in addition to lithium minerals, various brines also contain many other kinds of salts such as rare

metal compounds that can be comprehensively utilized. Liquid and solid evaporated salt-type lithium deposits around the world are almost all of them, although the other salts in each symbiotic and/or associated lithium deposit are different.

For example, the world's giant evaporated salt-type Salars lithium deposit located in the South American Lithium Triangle is a comprehensive deposit dominated by lithium and boron. Many salt lake brine-type lithium deposits in China contain salts such as magnesium, boron, lithium and rubidium compounds.

The same is true for various solid lithium deposits. Lithium is basically not isolated, but coexists and/or associates with various other rare metals, such as beryllium, rubidium, niobium, tantalum, gallium, cesium etc. Some contain tin or coexist with tin deposits.

Pegmatite lithium deposits without banded structures are usually considered to be independent lithium deposits. Even so, many such deposits are still accompanied by small amounts of rare metals such as beryllium and tantalum.

As for various sedimentary lithium deposits, they are mostly accompanied by gallium and rare earths.

In short, there are very few pure independent lithium deposits.

### **3 Genesis**

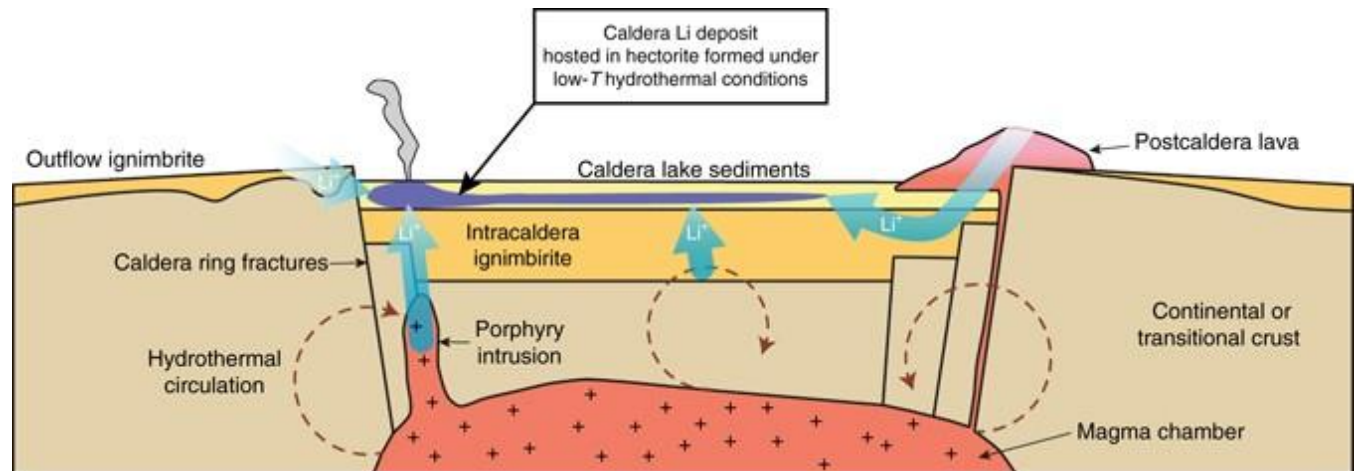
#### **3.1 Ore-forming material source**

Regarding the ore-forming material sources of global brine-type lithium deposits, there are currently several main understandings: lithium-containing hot springs or hot spring water related to volcanic activity and/or deep magma chambers are the main source of ore-forming materials for brine lithium deposits. Local solid lithium deposits, through weathering, denudation and leaching, also provides a material source for the formation of brine lithium deposits. Deep lithium-containing brine rises along deep faults and mixes with salt lake brine, promoting the enrichment and mineralization of brine lithium deposits.

When studying the formation mechanism of independent tellurium deposit in the world, the author of this article summarized the theory that rare elements are enriched and formed into deposits through the emission of mantle hot spots and/or mantle plumes and the nano-effect unique to nano-materials<sup>43-44</sup>. In other words, mantle emanation is one of the important sources of ore-forming materials, including endogenous lithium deposits such as pegmatite-type and exogenous sedimentary or even brine-type lithium deposits. Ore-forming materials rich in fluid and lithium from the upper mantle, with the help of the power of mantle emanation, enter the surface along deep faults and promote the formation of lithium deposits.

The known clay-type lithium deposits and endogenous lithium deposits such as volcanic lithium deposits in the world are closely related to magma, especially volcanic activity, in terms of their genesis<sup>2 & 22</sup>. The Salars lithium deposit in the central Andes of South America mentioned earlier in this article is not only located in a basin formed by frequent volcanic eruptions and faulting, but also contains ore-forming materials such as lithium and boron, which are derived from

volcanic rocks formed by multiple eruptions (Figures 2 & 5)<sup>22</sup>. Later hydrothermal/brine alteration is also one of the key factors in the formation of these lithium deposits.



**Figure 5.** Schematic model for the formation of caldera-hosted Li clay deposits

Rhyolitic magmas in continental settings have elevated Li concentrations such that eruptions voluminous enough to result in caldera collapse produce volcanic products with sufficient total Li to form economic deposits. Post-caldera magmatism contributes additional Li via lavas and outgassing of intrusions; it also generates hydrothermal systems focused along caldera ring fractures. Li is leached from ignimbrite and caldera-related lavas by meteoric and hydrothermal fluids and is deposited in hectorite clays formed within ash-rich caldera lake sediments<sup>2</sup>

### 3.2 Enrichment mechanism

The unique adsorption effect of carbon and some clay minerals<sup>45</sup> and the unique nano-enrichment effect of nanomaterial are two important mechanisms for the enrichment and mineralization of many rare, rare earth and precious metals including lithium<sup>43-44</sup>.

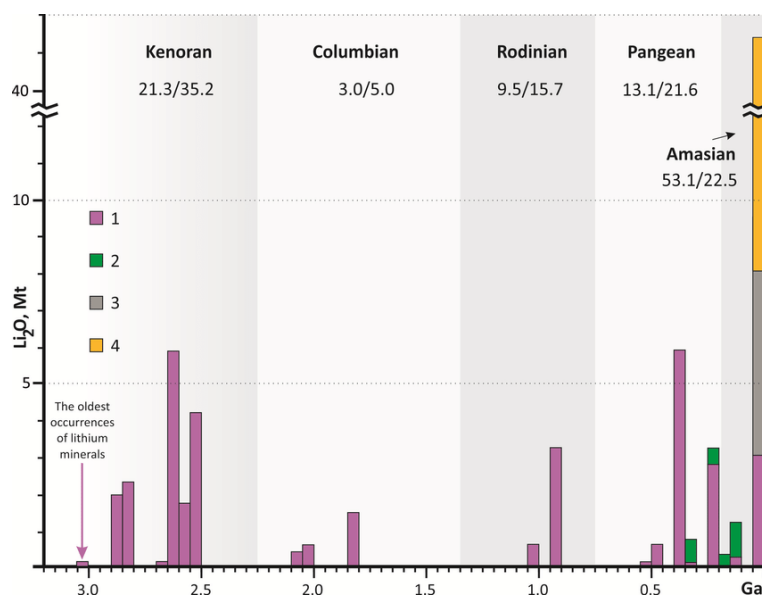
For exogenous brine and most sedimentary lithium deposits, the adsorption of carbonaceous and clay minerals is one of the most important mechanisms for lithium enrichment. The enrichment of ore-forming lithium from the upper mantle and lower crust through the nano-effect via upper mantle emanations is an auxiliary factor.

But for endogenous solid lithium deposits, the situation is just the opposite: lithium minerals enriched through the nano effect during the upper mantle venting is the main enrichment factor in the formation of these lithium deposits. Enrichment through carbonaceous materials such as graphite adsorption is an auxiliary factor.

Many ore-forming materials can be formed through the venting of mantle hotspots and/or mantle plumes, and through the nano effect enrichment unique to nano-scale materials. This theory is applicable to the enrichment mechanism of almost all endogenous metal deposits, especially those rare and rare earth metals with extremely low crustal abundance<sup>43-44</sup>.

### 3.3 Mineralization era

As for all types of lithium deposits on the earth as a whole, their mineralization era basically runs through the entire geological period, that is, from the Archean to the Quaternary, which is closest to humans (Figure 6). In other words, lithium deposits can be formed in various geological periods of the earth's evolution, although the frequency, intensity and type of lithium mineralization in different periods and different plates are obviously different. For example, brine-type lithium deposits are mainly the product of the Quaternary, which is also the mineralization era closest to humans. But this does not mean that there were no brine-type lithium deposits in the early geological history. Those ancient brine lithium deposits should have been transformed into solid endogenous and other exogenous lithium deposits along with corresponding geological tectonic activities such as orogeny.



**Figure 6.** Distribution of lithium resources accumulated in LSLDs through geological time

Note: A top number under a name of a supercontinent cycle shows a part (%) of the cycle in the total integrated resources of the analyzed selection, and a bottom one-the same value minus the resources of lithium-bearing salar brines. Key for LSLD types: 1-granite pegmatites, 2-Li-F rare-metal granites, 3-epithermal stratabound deposits, and 4-salar brines<sup>24</sup>.

### 3.4 Mineralization dynamics

The possible formation mechanism of brine lithium deposit is that in closed basins, especially closed basins in arid desert areas, lithium is enriched in brine under the adsorption of carbon and some clay minerals to form liquid lithium deposits with mining value.

The world-class giant liquid lithium deposits of Salar de Uyuni in Bolivia and Salar de Atacama in Chile are located in the desert of the western plateau of South America. The former was formed in the Cretaceous to Paleogene-Neogene, while the latter belongs to the Quaternary. The underground brine lithium deposits such as Sears Lake and Silver Peak identified in the Great

Basin between the Sierra Nevada Mountains and the Rocky Mountains in the western United States were all formed in the Cretaceous to Paleogene-Neogene (Figure 6).

As for sedimentary (and volcanic) lithium deposits, it is generally believed that they are related to volcanic activity. Volcanic ash is deposited under low temperature conditions in volcanic lakes to form clay-type deposits. The ore minerals are mainly hectorite and jadarite<sup>2 & 22</sup>.

The formation of most LCT-type pegmatites is genetically related to (syn-orogenic)-late orogenic peraluminous S-type, I-type or mixed S+I-type granites. Pegmatites formed directly by small-scale partial melting of crustal sedimentary rocks in the late orogenic and post-orogenic stages under extensional background intruded into typical low-pressure amphibolite-high greenschist phase metasedimentary rocks. The fine-grained and fine-grained rock structure and UST (unidirectional consolidation structure) in the outer zone of pegmatites, including the marginal zone, wall zone and fine-grained rock, are caused by the supercooling of the liquidus. The formation of coarse minerals, mineral zoning and saturated crystallization of rare metal minerals in the inner zone (intermediate zone, core zone) of pegmatites are the result of the accumulation of flux components (H<sub>2</sub>O, B, P, F) and rare metals (Li, Rb, Cs, Be, Nb, Ta) in the boundary layer through compositional zoning purification. The mineralization mechanism of LCT pegmatite-type rare metals mainly includes: fractional crystallization, magma immiscibility, supercritical fluid and compositional zonal purification. As for the origin of the full-vein mineralized spodumene pegmatite, it should be due to the strong distribution of lithium into the fluid phase.

China's solid lithium deposits are mainly pegmatite-type, concentrated in Xinjiang and Sichuan. The Mesozoic Era is the most important mineralization era, and the relatively stable tectonic environment after the intense orogenic movement is the most favorable mineralization background.

#### 4 Related topics

Exploring the types of lithium deposits and their genesis around the world is not for fun, but to provide a scientific basis for the search, exploration and development of such mineral resources. Accurately grasping the types of lithium deposits and the geological characteristics (ore-bearing rocks, alteration characteristics, mineral combinations, textures and structures, mineralization tectonic environment, etc.), geochemistry (related elements and their combinations, such as pegmatite deposits often contain a variety of rare elements Li, Rb, Cs, Be, Nb and Ta, etc.) and geophysics of various lithium deposits can provide a solid basis and sign for the discovery of more similar lithium deposits, so as to discover more lithium deposits more economically and efficiently, and make practical contributions to protecting the earth's environment and meeting human needs.

Based on the above lithium deposit types, it is necessary to delineate the prospecting target area that meets the geological conditions such as the known lithium ore host rocks, and then further determine the relevant anomalies and tectonic backgrounds through geochemical, geophysical measurements and remote sensing technology. It is the necessary basis for current lithium ore prospecting.



For example, although pegmatite-type lithium deposits around the world have certain commonalities, the differences between different pegmatite-type lithium deposits are also obvious. No two pegmatite-type lithium deposits are exactly the same. There are obvious differences in the mineral element combinations, host rock lithology, surface exposure, alteration types and the degree of zoning development of different pegmatites. These differences will naturally be reflected in geology, geophysics, geochemistry and remote sensing. Therefore, comprehensive information prospecting is still the general trend.

About five years ago, China conducted a nationwide large-scale survey on the spatial distribution of lithium geochemical anomalies based on the lithium content characteristics of different geological backgrounds, strata of different ages and different lithologies across the country. Then, based on the relevant survey results, that is, based on China's lithium geochemical background and its temporal and spatial distribution data, 31 relatively obvious lithium anomaly areas were discovered, and 19 lithium mineralization prospective areas were delineated, an increase of 7 from the previously delineated lithium mineralization prospective areas. The discovered lithium deposits (including underground brine-type and coal-related lithium deposits, etc.) are all located in these lithium anomaly areas<sup>46</sup>.

Li et al. divided the country into 12 lithium mineralization belts based on the distribution pattern of lithium deposits in China<sup>13</sup>:

- **Solid lithium mineralization belt:** Altai, Kangbal, West Tianshan, East Tianshan, West Kunlun, Songpan-Ganzi, Qinling, and South China mineralization belts.
- **Liquid lithium mineralization belt:** North Tibet, Qaidam, Sichuan Basin, and Jiangnan Basin mineralization belts.

According to Gruber and Medina of the University of Michigan<sup>6</sup>, brine-type lithium deposits account for 66% of the world's lithium resources, pegmatite-type lithium deposits account for 26%, and sedimentary rock-type lithium deposits account for 8%. In addition, clay-type and lacustrine evaporate-type lithium deposits also have potential for development.

One fact that cannot be ignored is that at the current rate of lithium consumption, all types of lithium deposits known around the world, especially brine lithium resources, are sufficient for human use for hundreds or thousands of years. However, the challenge we face with these liquid lithium resources is that the mining technology and extraction methods for some types of lithium deposits are still relatively weak and cannot keep up with the relevant demand. In addition, some brine and/or solid lithium deposits are not suitable for mining due to geographical restrictions. For example, China is rich in lithium resources, among which the amount of salt lake lithium resources is particularly huge. However, most of these liquid lithium deposits are located on the Qinghai-Tibet Plateau, which is sparsely populated and inconvenient for transportation. The conditions for development and utilization and related technologies are still a long way to go. In addition to geographical restrictions, China's related industries are facing practical problems such as the difficulty of solid lithium mining, the immaturity of lithium extraction technology from brine with a high magnesium/lithium ratio, and the need to import a large amount of deep-processed lithium products with advanced scientific and technological content and high performance from overseas.

In addition, at present and for a long time before, we have concentrated on mining solid pegmatite-type and liquid brine lithium deposits in America. The development of new types of

lithium resources such as sedimentary lithium deposits and lithium mica as the main industrial mineral is still extremely limited, and their investigation, research, development and utilization are still on the way. These new lithium deposits with huge potential resources are one of the important targets that need to be strengthened in related technological research, exploration and development now and in the future.

I believe that in the near future, the larger-scale application of lithium products will not be limited to the various lithium battery fields we know so far. With the continuous demand for new green energy, lithium isotopes as raw materials for controlled nuclear fusion will soon become a reality, and their use will be huge.

## 5 Discussion

From the perspective of mineralization time, lithium deposits can be produced in any period of the earth's 4.6 billion years of long geological history, from the oldest Archean to the current Cenozoic, although its types are divided into liquid and solid, and its causes are endogenous and exogenous.

Similar to any other mineral species on the earth's surface we are more familiar with, the spatial distribution of lithium deposits is seriously uneven. Instead, they are highly concentrated and occur in groups and/or belts.

There are numerous types of lithium deposits on the earth, including various endogenous solid lithium deposits, exogenous solid sedimentary, and various liquid brine lithium deposits. On the other hand, different types of lithium deposits have mutual conversion and even overlapping relationships, rather than either one or the other, no matter how different their surface morphology or manifestations are.

In addition to the known lithium deposit types listed in this article, it is believed that in the near future, we will also discover the following new types of lithium mineralization and even lithium deposits (Table 1): metamorphic lithium deposits, high-grade skarn-type lithium deposits, veinlet-dissemination lithium deposits related to granite intrusive like porphyry copper deposits, potassium feldspar ± sodium feldspar ± fluorite and/or quartz veins lithium deposits, and/or the combination type between these veins, etc.

## 6 Conclusions

The geochemical properties of lithium determine the diversity of its deposit types: there are various liquid brine lithium deposits on the ground (salt lakes) and underground (brine), as well as various solid lithium deposits formed by endogenous and exogenous mineralization.

In addition to the LCT pegmatite type, granite type, cryptoexplosive breccia type, claystone type, carbonate rock-claystone type, pneumatolytic hydrothermal type, coal-associated lithium and evaporate salt type that we have confirmed so far, I believe that in the near future, more new lithium deposits such as veinlet-dissemination type, various metamorphic types, skarn type, and potassium feldspar±albite±fluorite±quartz veins type will be discovered.

Currently known lithium ore resources, whether liquid brine type or various solid lithium ores, are mostly paragenetic and/or associated lithium deposits, which can be developed and utilized comprehensively. There are also real independent lithium deposits, but they are obviously pretty rare.

According to the current development status of global lithium deposits, brine-type, pegmatite-type and some sedimentary-type lithium deposits account for more than 90% of global lithium resources. Among them, brine-type lithium deposits are mainly concentrated in the "Lithium Triangle" in South America, LCT pegmatite-type lithium deposits are mainly concentrated in Australia, the United States, Canada and China, and sedimentary-type lithium deposits are mainly concentrated in Serbia, the United States, Mexico, China, Canada, Peru, Congo (Kinshasa), and Zimbabwe.

In terms of spatial distribution, lithium deposits are obviously heterogeneous and appear in local groups and belts. In terms of mineralization time, lithium deposits have been produced in various geological eras since the Archean. However, the types and quantities of lithium deposits in different geological periods are different, and brine-type and sedimentary rock-type lithium deposits are mostly developed in the Cenozoic.

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### Data availability

The data that support the findings of this study is available from the author upon reasonable request.

### Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Use of AI tools declaration



The author declares that he has not used Artificial Intelligence (AI) tools in the creation of this article.

