Issue 3
Volume 1
September, 2024

ISSN 2818-0313
DOI Prefix：10.62252

Naturalis

Scientias

www.naturalisscientias.com

TABLE OF CONTENTS

Original Articles

Short Report

Book Review

Original Article

Global lithium product applications, mineral resources, markets and related issues

JZ Yin[1,2,3] Ⓛ, Alice Shi[1], Haoyu Yin[4], Kuinuan Li[5] and Yuhong Chao[6]

Abstract

Lithium's natural genes, namely its chemical properties, determine its irreplaceable and important role in many fields of modern society, and also determine why it has become one of the hottest green energy metals today and is inseparable from our daily lives. Therefore, lithium deposits and lithium products have become one of the most concerned resources in the world in the past decade, and have also become a hot spot for investment in the international market. During this period, although the price of lithium products has occasionally fluctuated, it has generally been on the rise. Many visionary countries have listed lithium produced locally as one of the critical metals and strategic resources and restricted it to prevent foreign investors from getting involved. As far as the global lithium resources we have mastered so far are concerned, the theoretical quantity is already large enough and seems to be enough for human consumption for a long time. However, many known lithium deposits, especially the brine lithium deposits that account for the majority, are still facing the difficulties of lithium extraction technology and low extraction rate. In other words, for now and in the foreseeable future, the difficulty and urgency of lithium ore prospecting are not as urgent as improving lithium extraction technology as soon as possible. Looking into the future, lithium products will continue to occupy an important position in clean metal energy. Developing the nuclear energy contained in lithium isotopes will be one of the keys to achieving a leap in new energy technology in the future of human society.

Key words: lithium; chemistry and geochemistry; application; resource; extraction and preparation; market

---

Affiliation Info: [1] Orient Resources Ltd., Canada; [2] Wuhan Institute of Technology, Wuhan 430205, China; [3] College of Earth Sciences, Jilin University, Changchun 130061, China; [4] Guinea Westfield Mining Company, Plaza Diamant, kipe, Commune de Ratoma, Conakry-Guinee; [5] Henan Fanende Mining Co., Ltd., Luoning County, Luoyang City, 471700, China; [6] Engineering Geology Brigade, Jiangxi Bureau of Geology, Nanchang 330002, China

Article Info: Received: 16 August 2024 / Revised: 2 September 15 2024 / Accepted: 21 September 2024 / Published Online: 18 November 2024. www.naturalisscientias.com

Authors' Contact Info: Yin, JZ: jimyin7@yahoo.ca

Citation: JZ Yin, Alice Shi, Haoyu Yin, Kuinuan Li and Yuhong Chao. 2024. Global lithium product applications, mineral resources, markets and related issues. *Naturalis Scientias*, 1 (3): 197-217. DOI: https://doi.org/10.62252/NSS.2024.1015.

Corresponding AurhorⓁ: JZ Yin, PhD, PGeo, Professor; Email: jimyin7@yahoo.ca

1 Introduction

In recent decades, people have become more and more dependent on lithium batteries, and most people are becoming more and more familiar with rare metal lithium. The reason is simple. Our daily lives are increasingly closely related to electronic products related to lithium batteries, such as mobile phones, computers and other electronic products, and even the means of transportation that we cannot do without every day, especially various electric vehicles. They are inseparable from us humans and have to be in close contact with them almost every day.

Because of this, human enthusiasm for investing, finding and developing lithium and related metal deposits is getting higher and higher. The price of lithium products is naturally rising. Although there are some fluctuations in a certain period, the general trend has been rising.

The huge business opportunities covered by lithium products have also led more and more mining companies around the world to involve in the exploration and development of lithium deposits. Some internationally renowned mining companies have even turned from traditional bulk mineral deposits to the exploration and development of lithium deposits.

For example, on May 31, 2024, Chile’s state-owned company, the world’s largest copper miner, Codelco, signed a definitive agreement with the world’s second-largest lithium producer, Sociedad Química y Minera de Chile (NYSE: SQM), to jointly develop a giant lithium deposit in Chile’s Salar De Atacama. Sources say that the new deal gives Codelco a majority stake[1]. This is undoubtedly one of the key steps in Chilean President Gabriel Boric’s strategy to increase government control over lithium production. Prior to this, Chile announced a new policy to nationalize lithium mines. Máximo Pacheco, chairman of Codelco, said in a statement: “Just as we helped Chile become a global leader in copper production, we will now work to make Chile a global leader in lithium production.” Sociedad Química y Minera de Chile is a Chilean chemical company and a supplier of plant nutrients, iodine, lithium, and industrial chemicals.

Geologists who study, search, explore and develop different mineral deposits including lithium are also busy. They either help relevant mining companies to diligently search, explore and develop lithium deposits, study the geological and geochemical characteristics of the deposits, and search its mineralization laws in order to find more and better lithium deposits to meet the growing needs of human society. Similarly, mineral processing scientists have been experimenting and looking for the best technology for extracting lithium metal.

Of course, lithium metal is not the only energy metal known to humans. Our scientists are always looking for more efficient and environmentally friendly alternatives. We believe that a new generation of energy metals and/or semi-metals and related batteries will appear in the near future[2].

In any case, lithium is still indispensable in the new generation of energy metal batteries. Therefore, it is of great significance to discuss and summarize the global lithium resources and market status and related issues.

2 Chemistry and geochemistry

Lithium is derived from the Latin word λίθος, which means Lithos, i.e. rock or stone. Its chemical element symbol is Li, and its atomic number is 3. Under standard conditions, pure lithium is the least dense solid silvery-white alkali or lithium family metal. Lithium has a large charge density and a stable helium-type double electron layer, which makes it easy to polarize other molecules or ions, but itself is not easily polarized. Lithium is often in the oxidation state of +1 or 0, and is highly reactive and flammable. It is generally stored in a dry inert gas environment or kerosene in the laboratory. Fresh elemental metallic lithium has a metallic luster, but it quickly turns dark silver-gray in the air and then turns into a black oxide. As the least dense of all elements that are solids at room temperature, lithium can float on the lightest hydrocarbon oils and is one of only three metals that can float on water. Lithium does not occur freely in nature, but occurs mainly as pegmatic minerals, which were once the main source of lithium. Due to its solubility as an ion, it is present in ocean water and is commonly obtained from brines. Therefore, we can separate lithium metal from a mixture of lithium chloride and potassium chloride by electrolysis[3-5].

Lithium metal is soft enough to be cut with a knife. Its melting point of 180.50 °C and its boiling point of 1,342 °C are each the highest of all the alkali metals while its density of 0.534 g/cm3 is the lowest, comparable with pine wood . The nucleus of lithium is relatively unstable. It ranks 26th in content in the solar system and 27th in abundance in nature[3-6].

Although it was synthesized in the Big Bang, lithium, together with beryllium and boron, is markedly less abundant in the universe than other elements. Lithium is also found in brown dwarf substellar objects and certain anomalous orange stars. Certain orange stars can also contain a high concentration of lithium[7-9].

On February 19, 2015, the National Astronomical Observatory of Japan discovered that the nova explosion produced a large amount of lithium when observing the Delphinus Nova. This may mean that nova explosions may be the main mechanism for producing lithium in the universe[8].

Because of its relative nuclear instability, lithium is less common in the solar system than 25 of the first 32 chemical elements even though its nuclei are very light. For related reasons, lithium has important uses in nuclear physics. Lithium is a good conductor of heat and electricity as well as a highly reactive element, though it is the least reactive of the alkali metals. Molten lithium is significantly more reactive than its solid form[3-9].

Naturally occurring lithium is composed of two stable isotopes, 6Li and 7Li, the latter being the more abundant (95.15% natural abundance). Both natural isotopes have anomalously low nuclear binding energy per nucleon, compared to the neighboring elements on the periodic table, helium and beryllium. Lithium is the only low numbered element that can produce net energy through nuclear fission. The two lithium nuclei have lower binding energies per nucleon than any other stable nuclides other than hydrogen, deuterium and helium. Seven radio isotopes have been characterized, the most stable being 8Li with a half-life of 838 ms and 9Li with a half-life of 178 ms. Lithium isotopes fractionate substantially during a wide variety of natural processes, including mineral formation, metabolism, and ion exchange. Lithium ions substitute for magnesium and iron in octahedral sites in clay minerals, where 6Li is preferred to 7Li, resulting in enrichment of the light isotope in processes of hyperfiltration and rock alteration[8-11].

As a rare element, lithium exists in many rocks and brines, but the content is not high. There are quite a lot of lithium compounds in lithium minerals and brine, but relatively few of them have actual or potential commercial value. So far, we know of more than 30 kinds of lithium minerals, among which the main ones are spodumene, lepidolite, petalite, and hectorite clay. Spodumene and petalite are currently the most reliable commercial sources of lithium. Another important lithium mineral is lithium mica. A new source of lithium is hectorite clay, but currently only the Western Lithium in the United States is actively developing it[9-16].

Lithium constitutes about 0.002 percent of Earth's crust. Lithium is present in various igneous rocks, with the largest concentrations in granites. Granitic pegmatites provide the greatest abundance of lithium-containing minerals, with spodumene and petalite being the most commercially viable sources. Another source for lithium is hectorite clay[10-18].

Almost all vertebrate tissues and body fluids contain 21 to 763 ppb of lithium. Trace amounts of lithium are also found in many plants, plankton, and invertebrates, with concentrations ranging from 69 to 5,760 ppb. Among vertebrates, lithium marine organisms accumulate lithium more readily than terrestrial organisms. In addition, lithium is also present in soil and mineral water, cocoa powder, tobacco leaves, and seaweed. The total content of lithium in seawater is very large, estimated at 230 billion tons, and it exists in a relatively constant content of 0.14 to 0.25 ppm. Higher levels approaching 7 ppm have been found near hydrothermal vents on the seafloor.

In 1800, Brazilian chemist and politician José Bonifacio de Andrada discovered petalite in a mine on the Swedish island of Utö. But it was not until 1817 that Johann Arfvedson discovered the new element while analyzing the mineral petalite in the laboratory of chemist Jöns Jacob Berzelius. The element's compounds are similar to those of sodium and potassium, but its carbonates and hydroxides are less soluble in water and less alkaline. Berzelius named the alkali metal "lithion/lithina", which translates to lithos, to reflect the fact that it was found in a solid mineral[15-18].

Arfvedson later discovered that both spodumene and lepidolite contain this element. In 1818, Christian Gmelin first discovered that the flame color of burning lithium salts is bright red, but neither Arfvedson nor Gmelin were able to separate pure lithium from its salt. It was not until 1821 that elemental lithium was obtained when William Thomas Brand electrolyzed lithium oxide. This method was used by chemist Humphry Davy to separate alkali metals potassium and sodium. In 1855, Augustus Matthiessen produced more metallic lithium by electrolyzing lithium chloride. In 1923, the German company Metallgesellschaft AG borrowed this method to produce commercial lithium by electrolyzing a mixture of molten lithium chloride and potassium chloride. Since then, the production and use of lithium has undergone several drastic changes[17-25].

3 Application

Lithium and its compounds have several industrial applications, including heat-resistant glass and ceramics; lithium grease lubricants; flux additives for iron, steel and aluminium production; lithium metal batteries and lithium-ion batteries. These uses consume more than three-quarters of lithium production. Lithium-based drugs are useful as a mood stabilizer and antidepressant in the treatment of mental illness such as bipolar disorder. Lithium has a mass specific heat capacity of 3.58 kilojoules per kilogram-kelvin, the highest of all solids. Because of this, lithium metal is often used in coolants for heat transfer applications[25].

The first major use of lithium was in high temperature lithium greases for aircraft engines and similar applications during World War II and shortly thereafter. Lithium soaps have a higher melting point than other alkaline soaps and are less corrosive than calcium soaps. The demand for lithium soaps and greases has led to the creation of several small lithium mining operations in the United States[15-26].

Both ^{6}Li and ^{7}Li produce tritium when irradiated by neutrons. As a result, the demand for lithium increased dramatically during the Cold War as nuclear fusion weapons were produced. Lithium can also be used as a solid fusion fuel for hydrogen bombs in the form of lithium hydride. For this reason alone, the United States became the world's leading lithium producer between the late 1950s and the mid-1980s.

When using the Hall-Heroult process, lithium is used to lower the melting temperature of glass and improve the melting behavior of alumina. These two uses dominated the market in the mid-1990s17-19, 23-25 & 27-33. In the mid-1990s, several companies began extracting lithium from brines, which was cheaper than mining solid lithium ore underground or in open pits. However, due to low demand in the local market, most lithium mines closed.

Nuclear weapons manufacture and other nuclear physics applications are a major source of artificial lithium fractionation, with the light isotope ^{6}Li being retained by industry and military stockpiles to such an extent that it has caused slight but measurable change in the 6Li to ^{7}Li ratios in natural sources . The transmutation of lithium atoms to helium in 1932 was the first fully human-made nuclear reaction, and lithium deuteride serves as a fusion fuel in staged thermonuclear weapons[25].

According to the United States Geological Survey34, the global end-use market for lithium in 2019 was: batteries 65%, ceramics and glass 18%, lubricants 5%, polymer production 3%, continuous casting flux 3%, air treatment 1%, and others 5%. Over the past 10 years, the share of lithium consumption in the battery market has nearly tripled. Obviously, batteries are the fastest growing industry for lithium consumption.

In recent years, the need for a green and low-carbon economy and the introduction of relevant international treaties have accelerated the international community's demand for lithium, a resource with good physical and chemical properties. The output and consumption of lithium ore have shown a rapid increase overall, and it has become a strategic critical mineral generally recognized by the international community. It is widely used in emerging fields such as batteries, medicine, nuclear industry, aerospace, new energy vehicles, etc., and has shown great potential in controlled nuclear fusion power generation, because 1 gram of lithium is equivalent to 3.7 tons of standard coal[17-19, 23-25 & 27-34].

Lithium has a very small atomic weight, and the battery used as the anode has a high energy density. Lithium can also be used to make low-temperature and/or high-temperature batteries. Lithium batteries used for low temperatures usually use organic solvents as electrolytes, and inorganic salts are added to make them more conductive. Commonly used inorganic salts include lithium perchlorate, lithium hexafluorophosphate, lithium hexafluoroarsenate, and lithium sulfide. The positive electrode materials in secondary lithium batteries are also lithium-containing compounds and their multi-component compounds, such as lithium cobalt oxide, lithium nickel oxide, lithium manganese oxide, lithium iron oxide, etc. The cathode of the battery is lithium, and the anode is often a metal chloride. For example, the battery chemical reaction formula of a lithium-silver chloride battery is: $\mathrm{Li + AgCl \rightarrow LiCl + Ag}$. Lithium batteries used for high temperatures usually use molten inorganic salts as electrolytes, but they must be used above the melting point of the salt. The relevant reaction formula is: $\mathrm{2Li + 2Cl \rightarrow 2LiCl}$.

There is no doubt that the vigorous development of lithium batteries has dramatically increased the demand for lithium worldwide, and it became the main use of this substance in 2007. With the surge in human demand for lithium batteries, many mining companies around the world have expanded the exploration and mining of brine lithium mines. Some people believe that lithium will become one of the main objects of geopolitical competition in a world dependent on renewable energy and batteries[28-30 & 34-35].

In medical terms, lithium is an effective treatment for seborrheic dermatitis. This may be related to the fact that lithium can inhibit substance-P and all free fatty acids required for the growth of Malassezia yeasts. Some studies have shown that lithium can inhibit many enzymes: such as Na/K ATPase, adenylcyclase, enzymes of the prostaglandins E1 synthesis, and inositol-1-phosphatase. Lithium also has anti-inflammatory and immunomodulatory effects. Oral lithium-containing drugs are mainly used to treat bipolar disorder, but this type of oral drug can cause many side effects on the skin. Relevant research in France shows that lithium-containing hot spring water (Evaux thermal spring water) can improve patients' side effects of skin and nail lesions caused by cancer treatment[17, 25 & 34].

Lithium can also be used as a synthetic raw material, a reducing agent, a catalyst, a heat carrier for manufacturing nuclear reactors in the atomic energy industry, and used to manufacture special alloys and special glasses. It can also be used as a deoxidizer, desulfurizer, and defoamer in the metallurgical industry, as a fuel, and as the red part of fireworks that people love to see. It can also be used to launch weapons such as torpedoes. Alloys doped with lithium have the characteristics of high strength, low density, and high temperature resistance. Some people have also used lithium to synthesize lithium-lead liquid semiconductor alloys.

4 Resource

According to statistics from the United States Geological Survey, the total global lithium reserves are approximately 31,000 tonnes25 & 34. Other researchers have given similar results on the reserves (Figure 1)[35].

Chile is estimated to have the largest reserves by far (9.2 million tonnes), and Australia the highest annual production (40,000 tonnes). One of the largest reserve bases of lithium is in the Salar de Uyuni area of Bolivia, which has 5.4 million tonnes. Other major suppliers include Australia, Argentina and China25 & 34-38. As of 2015, the Czech Geological Survey considered the entire Ore Mountains in the Czech Republic as lithium province. Five deposits are registered, one near Cínovec is considered as a potentially economical deposit, with 160,000 tonnes of lithium[12, 25 & 34].

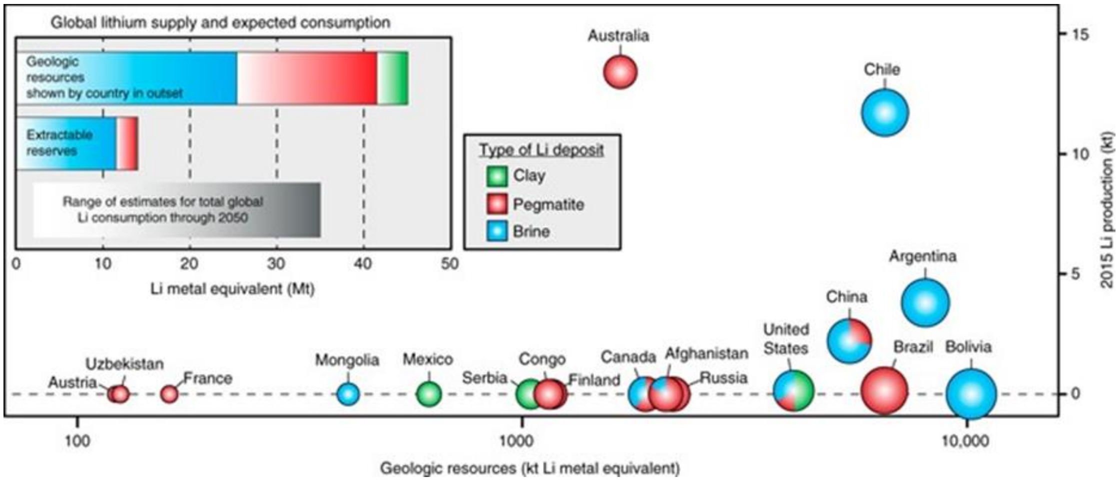


Figure 1. Global lithium resources and total 2015–2050 estimated consumption

Estimates for global Li resources are ~45 Mt Li and include brine, pegmatite, and clay resources. Global Li reserves (the amount of the resource that is currently economically extractable) are estimated at ~14 Mt Li, primarily from brine and clay deposits. Future Li consumption (2015–2050) estimates range anywhere from 3–35 Mt Li, depending on the efficiency of Li extraction and projections for electrification of the automobile industry, highlighting the need to explore for new resources of Li[35]

In June 2010, The New York Times reported that American geologists were conducting ground surveys on dry salt lakes in western Afghanistan believing that large deposits of lithium are located there. These estimates are "based principally on old data, which was gathered mainly by the Soviets during their occupation of Afghanistan from 1979–1989". The Department of Defense estimated the lithium reserves in Afghanistan to amount to the ones in Bolivia and doubled it as a potential "Saudi-Arabia of lithium"39 & 40. In Cornwall, England, the presence of brine rich in lithium was well known due to the region's historic mining industry, and private investors have conducted tests to investigate potential lithium extraction in this area[25].

The total lithium content of seawater is very large and is estimated as 230 billion tonnes, where the element exists at a relatively constant concentration of 0.14 to 0.25 ppm, higher concentrations approaching 7 ppm are found near hydrothermal vents[25 & 34].

The world's lithium resources are rich but highly concentrated, with 73% of lithium resources distributed in South America and North America. Oceania, Asia, Europe and Africa have relatively few lithium resources, accounting for 8%, 7%, 7% and 5% respectively (Figures 1 & 2). In terms of countries, lithium resources are mainly distributed in Bolivia, Chile and Argentina in the "Lithium Triangle" region of South America. It is currently known that lithium mines around the world are distributed in 6 large concentration areas, belonging to 23 countries.

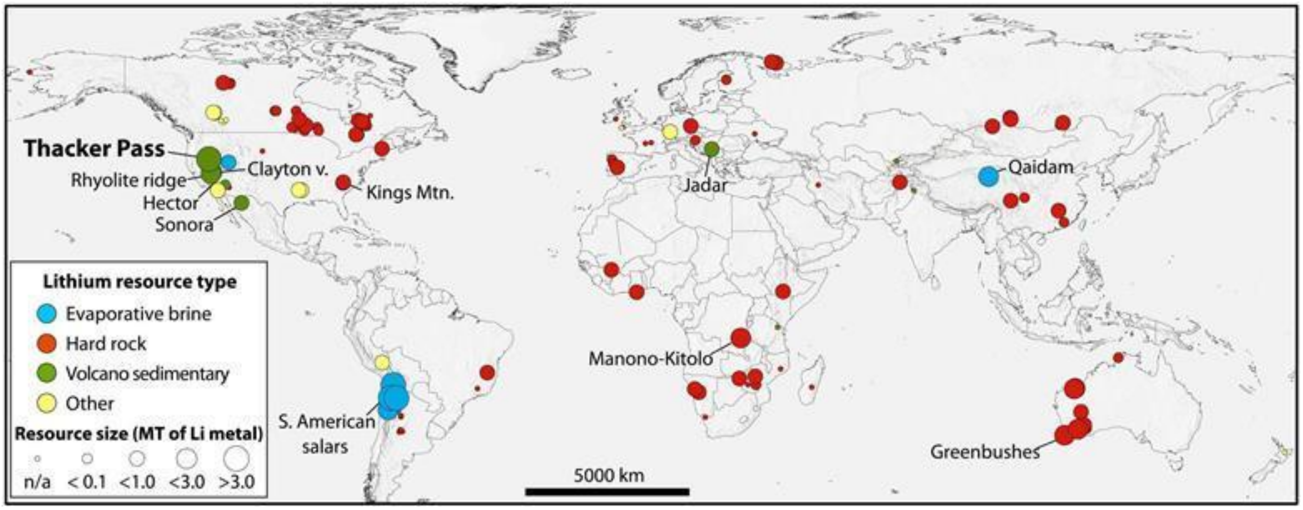


Figure 2. Map showing type and relative size of global lithium resources[41]

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

In terms of reserves, the world's proven lithium reserves were 17 million tons in 2019. Among them, Chile's lithium reserves ranked first in the world, about 8.6 million tons, accounting for 50.59% of the world's total reserves, far ahead of other countries. Australia ranks second, about 2.8 million tons, accounting for 16.47% of the world's reserves. Argentina ranks third, about 1.7 million tons, accounting for 10.0% of the world's reserves. China ranks fourth, about 1 million tons, accounting for 5.88% of the world's reserves. The lithium reserves of the above four countries account for about 85% of the world's total reserves. It is followed by the United States, Canada, Zimbabwe, Brazil and Portugal (Figures 1, 2 & 3)[25, 34-36 & 40-47].

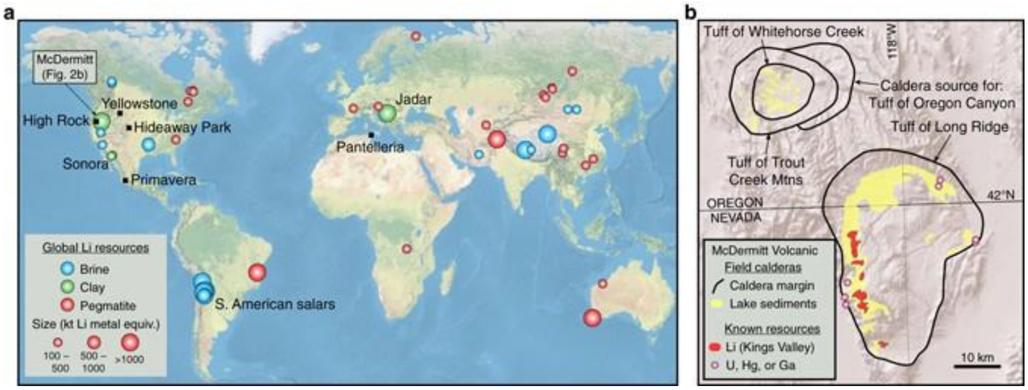


Figure 3. Location maps of global lithium resources and McDermitt volcanic field

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[35]

In terms of lithium resources, 58.75% of the world's lithium is concentrated in the "Lithium Triangle" countries in Latin America, and the lithium resources in the United States, Australia and China account for 8.5%, 7.9% and 5.6% of the world's total, respectively.

Comparing the two different sets of data on reserves and resources, it can be seen that the United States, China, Bolivia and Argentina have great potential for the development and utilization of lithium deposits.

It should be pointed out that although lithium resources are very rich, many lithium resources cannot be converted into lithium reserves due to mining conditions and lithium extraction technology. For example, Uyuni, the world's largest known lithium mine, has a huge amount of lithium resources that cannot be included in lithium reserves because there is no economically feasible method for extracting lithium salts at this time[40-47].

Currently, nearly 30 countries around the world are conducting lithium exploration activities. Among them, Australia, the United States and Canada are the three most active countries in lithium exploration activities, with about 210 related exploration projects. In addition, there are 21 in Latin America, 25 in Africa, 24 in Europe, and only 6 in Asia excluding China.

The top ten lithium deposits in the world are Bonnie Claire, Vulcan, Clayton Valley, Kachi, Mt Holland-lithium, Pozuelos, Phyolite Ridge, Cuenca Centenario-Ratones, Tetra and Pastos Grandes (Figures 2 & 3).

China has discovered 153 lithium deposits/showings in more than 10 provinces (regions). Solid lithium deposits are mainly distributed in 14 provinces (regions), including Inner Mongolia, Henan, Shanxi, Jiangxi, Sichuan, Fujian, Xinjiang, Guizhou, Yunnan, Shaanxi, Guangxi, Guangdong, Hubei and Hunan. Liquid brine lithium deposits are concentrated in 6 provinces (regions), including Xinjiang, Qinghai, Tibet, Sichuan, Inner Mongolia and Hubei[47-53].

According to the information currently available, there are a total of 6 important lithium mining belts in all continents of the world[40-53].

4.1 North American lithium belt

- Whabouchi pegmatite lithium deposit in Quebec, Canada, with a total resource of 49.12 million tons, containing 744,800 tons of lithium and a grade of 1.52%.
- The pegmatite-type lithium deposits in Quebec, Canada and its northern James Bay have lithium resources of approximately 47 Mt (average lithium content of 0.23%, equivalent to 0.11 Mt lithium) and 22.20 Mt (average lithium content of 0.58%, equivalent to 0.13 Mt lithium), respectively.
- King Mountain pegmatite lithium deposit in Cleveland, North Carolina, USA, estimated at 20% spodumene content, ore Li_2O content is about 1.5%, the entire North Carolina pegmatite belt Li_2O reserves are about 1 Mt.
- Kings Valley sedimentary lithium deposit in Nevada, USA, with a total resource of 234 million tons, containing 1.560 million tons of lithium, a total reserve of 27.14 million tons, containing 231,000 tons of lithium, and a lithium grade of 0.85%.

- Silver Peak salt lake lithium mine in Nevada, USA, with Li_2O reserves of about 115,000 tons.

4.2 Oceania lithium belt

- Green bushes pegmatite lithium deposit in Yelgon Province, Australia, with lithium ore resources of 7.1 Mt, Li_2O grade of 4.06%; tantalum ore of 47 Mt, Ta grade of 0.06%; niobium ore of 10.8 Mt, Nb grade of 0.42%; tin ore of 4.7 Mt, Sn grade of 0.24%; kaolin ore of 2.3 Mt, kaolin grade of 30.00%.
- Mount Myrion pegmatite lithium mine in Yelgon Province, Australia, with spodumene reserves of 1 Mt and an average Li_2O content of 1.7%.
- Pilgangoora pegmatite lithium deposit in Australia, with a lithium resource of 983,000 tons.

4.3 African lithium belt

- The Bikita pegmatite lithium deposit in Fort Victoria, Zimbabwe, is divided into two mining sections: Bikita and El Hait. The Bikita mining section has a lithium ore reserve of 6 Mt and an average Li_2O content of 2.9%, mainly mining lepidolite; the El Hait mining section focuses on mining petalite, with a lithium ore reserve of 2.6 Mt and an average Li_2O content of 4.1%.
- Kamativi pegmatite lithium deposit in Zimbabwe, with an estimated resource of 100 Mt, an average lithium content of 0.28%, equivalent to 0.28 Mt of metallic lithium.
- The Manono and Kitotolo pegmatite lithium deposits in Katanga Province, Congo (DRC) have an estimated Li_2O resource of 11.45 million tons, of which Manono contains 835,000 tons of Li_2O resources and Kitotolo contains 310,000 tons of Li_2O resources.

4.4 European lithium belt

- Jadar sedimentary lithium deposit in Belgrade, Serbia, with a total resource of 125.3 million tons, 2.26 million tons of lithium and a lithium grade of 1.8%.
- The Cinovec pegmatite lithium deposit in the Bohemian Plateau of the Czech Republic has a lithium resource of 1.19 million tons.
- Wolfsberg pegmatite lithium deposit in Austria, with a lithium resource of 264,000 tons.

4.5 Latin America and South America lithium belt

This lithium ore belt is mainly rich in liquid brine lithium deposits, including the internationally renowned "Lithium Triangle". However, the author believes that large solid lithium deposits will be discovered in South America in the near future.

4.6 Asian lithium belt

The so-called Asian lithium mining belt is currently mainly concentrated in China. China's lithium reserves and resources are among the highest in the world, but it lacks high-grade, high-quality lithium deposits. The country's lithium resources are mainly concentrated in Qinghai, Tibet, Sichuan, Jiangxi, Hubei and Hunan provinces. The lithium resources in these regions account for 99.9% of China's proven resources. Among them, solid lithium deposits are concentrated in Sichuan, Jiangxi, Hunan, Xinjiang and other provinces (regions), while salt lake brine-type lithium deposits are concentrated in Qinghai, Tibet and Hubei provinces (regions). China's salt lake brine-type lithium deposits have low lithium content, and most of them are distributed in the plateau areas such as Qinghai and Tibet with weak infrastructure and poor mining conditions. This has led to a low development and utilization rate of lithium resources in China, and a significant lack of self-sufficiency[28, 34-36, 38, 40-45 & 47-54].

5 Extraction and preparation

5.1 Extraction[17-18, 25, 34, 51-53 & 55-62]

- **Sulfate method**: After spodumene and potassium sulfate are sintered together, potassium will replace lithium to form lithium sulfate that is soluble in water. The chemical reaction equation is as follows: $2LiAl(SiO_3)_2 + K_2SO_4 \rightarrow Li_2SO_4 + 2KAl(SiO_3)_2$. For a long time, sulfate extraction was the only method for industrial preparation of lithium. This method is not only applicable to spodumene, but can also be used to treat lithium mica, etc.
- **Lime method**: Lime or limestone is sintered with lithium ore at a temperature of 1,000°C and then treated with water. The leaching solution is evaporated multiple times to crystallize lithium hydroxide. The chemical reaction formula is as follows: $2LiAl(SiO_3)_2 + 9CaO \rightarrow Li_2O + CaO{\bullet}Al_2O_3 + 4[2CaO{\bullet}SiO_2]$. The advantages of this method are: strong applicability and ability to decompose almost all different kinds of lithium ores; the reaction does not require scarce raw materials; and lime and limestone are both cheap and easy to obtain. The disadvantages are: a dilute solution is obtained after leaching, and evaporation consumes a lot of heat and takes a long time.
- **Sulfuric acid method**: Ellestad and Leute first developed this method. The sulfuric acid method is applicable to β-spodumene and lepidolite. Under the temperature conditions of 250-300 ℃, the relevant lithium minerals react with sulfuric acid as follows: $2LiAl(SiO_3)_2 + H_2SO_4 \rightarrow Li_2SO_4 + H_2O{\bullet}Al_2O_3{\bullet}4SiO_2$. The problem with this method is that sulfuric acid only reacts with β-spodumene, but not α-spodumene. Direct decomposition of uncalcined spodumene with sulfuric acid only extracts 4% of the total lithium.
- **Extraction of natural brine**: The processing process is to precipitate the lithium in the natural brine into Li_2NaPO_4, and then convert it into lithium carbonate, which can be used as a raw material to process other lithium compounds. Processing natural brine can also produce by-products such as borax, potassium carbonate, sodium chloride, sodium sulfate and magnesium chloride.

5.2 Preparation of lithium metal[17-18, 25, 34, 51-52 & 55-62]

At present, there are the following methods for preparing metallic lithium:

- **Electrolysis**: Metallic lithium is obtained by electrolyzing molten lithium chloride. Graphite is used as the anode, low-carbon steel is used as the cathode, and the electrolytic cell pressure is 6.0-6.5 V. This will produce lithium with a purity of 99%. Metallic lithium obtained by electrolysis usually contains impurities such as Na, K, Mg, Ca, Fe, Si and Al, and needs to be purified. These impurities can be filtered out by remelting and using the difference in specific gravity. As for the sodium and potassium that are difficult to remove, they can be removed by hydrogenation.
- **Thermal reduction method**: The chemical reaction formulas are: $3Li_2O + 2Al \rightarrow 6Li + Al_2O_3$，$2Li_2O + Si \rightarrow 4Li + SiO_2$. Reduction of lithium oxide is an endothermic reaction and can only be carried out at high temperature and high vacuum。

6 Market[34, 41, 43-53 & 63-66]

As an important new energy metal, lithium plays an increasingly important role in lithium batteries, new energy vehicles and controlled nuclear fusion. Due to its important strategic significance, the world has set off a wave of exploration and development of lithium mineral resources. Some people even call 2016 the "Global Lithium Mineral Exploration Year". Compared with the sluggish market of bulk minerals, lithium mineral resources have become a hot spot in the market.

The global lithium consumption has steadily increased from 113,000 tons of lithium carbonate equivalent in 2010 to 310,000 tons of lithium carbonate equivalent in 2019. It has increased by 174.3% in the past 10 years. In recent years, the global lithium salt consumption has shown a more rapid growth momentum, with an average annual growth rate of 17.6% (Figure 4).

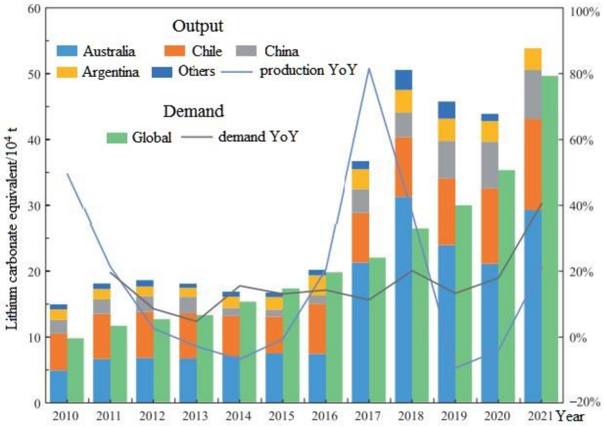


Figure 4. Lithium product production, demand and comparison of major countries in the world from 2010 to 2021[28 & 34]

In the foreseeable future, global consumption of lithium products will continue to grow (Figure 1).

Lithium products refer to metal lithium and lithium compounds such as lithium carbonate, lithium hydroxide and lithium chloride. Among them, lithium carbonate is the most direct lithium product formed after lithium ore mining and processing.

Before 2016, although lithium products were widely used in metallurgy, ceramics, glass, lubricants, organic chemistry, pharmaceutical products, mobile phone batteries and other fields, the usage was small and the price has been hovering at a low level. In recent years, the battery field has become the core driving force for the growth of lithium demand, and the scale of new energy vehicles has expanded significantly, driving lithium prices to continue to rise.

Since 2016, the global supply of lithium products has been tight and prices have risen rapidly. Since 2018, lithium products have experienced excess production capacity, and lithium product prices have fallen. Affected by the epidemic in the first half of 2020, lithium product prices fell to a low point. Starting from the second half of 2021, countries have increased their emphasis on new energy technologies, and the global new energy market has exploded. Demand for lithium products has continued to remain high, and as a result, supply has been insufficient, and prices have continued to rise and premiums have appeared.

In addition to lithium concentrate, the historical price trends of lithium products such as lithium carbonate and lithium hydroxide are basically the same whether in Asia, Europe or North America. The price was at the bottom in October 2020 (about US$10,000/ton), and then increased rapidly, once exceeding US$50,000/ton in 2022. Among them, the Chinese market price leads the way, once exceeding US$75,000/ton.

Australia is the world's largest supplier of lithium concentrate and the main source of China's spodumene concentrate imports, accounting for 95.4% of China's total lithium concentrate imports in 2021. More than 95% of the world's lithium concentrate is imported by China, increasing from 5.0×10^4 tons in 2012 to 26.3×10^4 tons in 2021, an increase of 426%. Among them, 95.4% of lithium concentrate in 2021 came from Australia, and the remaining 4.6% came from Brazil.

Before October 2020, due to factors such as oversupply and the COVID-19 pandemic, the long-term price of Australian lithium concentrate continued to decline to US$385/ton. After that, it bottomed out and grew rapidly. It reached US$3,700/ton in May 2022, an increase of 861%. Since 2021, Pilbara Mining has completed spot auctions of lithium concentrate through the BMX platform many times. Among them, the prices of the first four auctions were 70%, 121%, 83% and 69% higher than the long-order prices of the day, respectively. They played a significant guiding role in the price expectations of the lithium market and quickly pushed up the prices of lithium products.

In 2021, the United Kingdom and the United States successively launched lithium futures markets, continuing to increase their influence and voice on lithium pricing. Although China has also begun to plan its own lithium pricing and trading methods, its pace is relatively backward. In July 2021, Wuxi Electronic Trading launched a lithium carbonate forward contract, but the lithium carbonate contract is not a futures contract in the traditional sense. In November of the same year, the relevant person in charge of the Guangzhou Futures Exchange said that the exchange's lithium futures had been approved by the China Securities Regulatory Commission, but it would take some time to go online.

China is the world's largest lithium trading and consumer country, but its influence on the international pricing of lithium is limited. Since 2007, China's net imports of lithium carbonate have generally been on the rise. From 2007 to 2017, the total net imports of lithium carbonate in the country were 102,700 tons, of which the net imports in 2017 reached 29,200 tons. 63.70% of the imports came from Chile and 29.80% from Argentina. From 2010 to 2021, China's lithium carbonate imports grew rapidly, from 0.64 × 10^4 tons in 2010 to 8.1 × 10^4 tons in 2021, an increase of 11.7%.

In addition, as the main raw material for the production of metallic lithium, China's domestic lithium chloride production is extremely small and relies heavily on imports. From 2009 to 2015, the country's cumulative net import volume reached 21,800 tons.

From 2007 to 2017, China's total lithium product consumption reached 624,300 tons, with an average annual growth rate of 19% in 11 years. Among them, China's lithium product consumption in 2017 was 124,700 tons, accounting for about 52.48% of the world's total consumption of 237,600 tons that year. Compared with the consumption of 22,800 tons in 2007, it increased by 101,900 tons, an increase of 81.72%. In China's lithium product consumption in 2017, lithium used in the battery field ranked first, accounting for as high as 67%. Glass ceramics, medicine, grease and catalyst ranked second, third, fourth and fifth, accounting for 7%, 6%, 6% and 3% respectively, and the five together accounted for about 86% of the total lithium consumption.

Comparing the production and consumption of lithium products in China from 2007 to 2017, it can be seen that the domestic production of lithium products is significantly lower than the consumption, but both maintain a rapid growth trend. Over time, the gap between the production and consumption of lithium products will continue to widen.

China is rich in lithium resources, but battery-grade lithium carbonate, high-purity lithium carbonate, anhydrous lithium chloride and high-purity metallic lithium with high technical content still need to be imported in large quantities, reflecting the low efficiency of China's lithium resource development and utilization and the severe situation of resource security.

Since 2019, China's consumption of lithium products has exceeded 55% of the world's total, making it the world's largest consumer of lithium products. In recent years, China's imports of lithium carbonate and lithium concentrate have ranked first in the world. In 2021, China's lithium product consumption was about 39.3 × 10^4 tons of LCE, accounting for about 72% of the world's total production. Among them, China's domestic production was 13.0 × 10^4 tons, and imports were 34.7 × 10^4 tons. The external dependence of lithium resources was as high as 67% (external dependence = (consumption-production)/consumption).

As the world's largest consumer of lithium products, China's domestic lithium ore quality is poor and the development cost is high, which has caused the spot price of lithium products in China to be higher than the international level.

In contrast, China's lithium carbonate exports have remained at a low level. Before 2018, the annual export volume was less than 0.5 × 10^4 tons, and it increased slightly after 2018.

China's lithium hydroxide imports have always been at a low level. The average annual import volume from 2010 to 2021 was only 0.07 × 10^4 tons, accounting for less than 1% of global imports each year.

In contrast, as one of the world's most important lithium salt production bases, China's lithium hydroxide exports continue to increase. In addition to meeting domestic demand, the lithium hydroxide it produces is also exported in large quantities, and China's lithium hydroxide exports have ranked first in the world. In 2016, 9,800 tons of lithium hydroxide were exported, an increase of 6,100 tons from 3,800 tons in 2007, an increase of 61.51%. Then it increased from 0.25 × 10^4 tons in 2010 to 7.36 × 10^4 tons in 2021, an increase of nearly 28 times. It supplies more than 80% of the lithium hydroxide currently needed in the world.

The main reason for this phenomenon is that lithium hydroxide is mainly derived from spodumene, and the mineral processing and extraction process of brine-type lithium ore requires the preparation of lithium carbonate first, and then the generation of lithium hydroxide. Restricted by development conditions, technology, cost and other factors, the mining of brine lithium deposits in China has developed slowly and there is a large gap in the output of lithium carbonate. However, the lithium hydroxide produced by the country's pegmatite-type lithium mines has cost advantages, resulting in a situation where its lithium hydroxide imports are low and exports are high.

Europe and the United States have obvious resource advantages and a vast terminal automobile market. They are currently working hard to increase processing capacity and try to build their own supply chain closed loop.

There are many problems in China's lithium product market, including but not limited to the following aspects: most lithium deposits have poor development conditions, low lithium deposit development and utilization rates, serious homogeneity of lithium battery companies, low industrial concentration, insufficient extension of the industrial chain, uneven development of various links, imperfect industrial chain structure, and low degree of integration. In addition, China's financial support for promoting international capacity cooperation is insufficient, and the financial market has insufficient development, high financing costs, single channels, high thresholds for equity funds, imperfect financial infrastructure, lagging financial services development, and lack of effective regional financial markets. Furthermore, China's lithium product companies have serious inadequacies in internationalization capabilities and mutual coordination between companies, and have not formed a joint force. Basically, they are fighting alone.

Stimulated by the current high lithium price, the supply side of lithium products continues to expand, the investment in lithium ore exploration has increased significantly, the beneficiation and processing and salt lake lithium extraction technologies have achieved breakthroughs and improvements, and the secondary recycling industry has developed rapidly.

It is believed that in the next 3-5 years, the commissioning or increased production of lithium mines such as Greenbush, Wogina, Mt. Holland in Australia and Tres Quebradas (3Q), Cauchari, and Cionbre Muerto in South America will effectively increase the global supply of lithium products. The global supply and demand pattern may be greatly improved as a result, and it is expected to change from shortage to oversupply, thereby driving down the price of lithium products.

Since 2007, China's lithium product output has grown rapidly, with an average annual growth rate of 128%. From 2007 to 2017, the country's cumulative lithium production was 573,500 tons (lithium carbonate equivalent LCE, the same below). Among them, the national lithium product output in 2017 reached 96,000 tons, accounting for about 41.9% of the world's total output of 229,000 tons that year. However, China's demand for lithium products still mainly depends on imports. In 2017, China's lithium supply structure was as follows: 79,200 tons of spodumene ore was imported from Australia, accounting for 57%; 35,600 tons of high-concentration brine lithium ore was imported from Latin America, accounting for 23%. In 2018, China's lithium ore output reached 80,000 tons, a year-on-year increase of 17.6%. However, most lithium deposits are distributed in the Qinghai-Tibet Plateau, and the magnesium/lithium ratio of brine lithium ore in the Qaidam Basin in Qinghai is high, and the lithium extraction technology is not yet mature.

The development and utilization of lithium deposits are subject to dual constraints of the environment and technology, so the raw ore is highly dependent on foreign countries.

7 Discussion

There is no doubt that with the passage of time and the rapid rise of the three major industries of new energy, new materials and new medicines, the development and utilization of lithium resources, as a new clean green high-energy metal and known as "white oil", will surely receive more and more attention and importance from major countries in the world.

In addition, more and more governments and mining companies will further increase the exploration and development of lithium deposits. There will also be more countries that control and reserve lithium as a critical metal and strategic resource.

Whether it is lithium mining technology or mineral processing and extraction technology, innovation and breakthroughs are needed. In particular, for those brine lithium deposits with high magnesium/lithium ratios and many associated elements, breakthroughs in this area need to be made as soon as possible. Otherwise, these liquid lithium deposits with huge potential lithium resources can only become idle and waste deposits and cannot be mined and utilized. In other words, it is necessary to increase the innovation of brine lithium extraction technology in order to achieve large-scale production of lithium resources in difficult areas such as the Qinghai-Tibet Plateau.

China's salt lake lithium resources account for about 80% of the country's total lithium reserves, but China's salt lake lithium extraction capacity accounted for only 21.5% in 2020. Limited to brine lithium extraction technology, a large amount of salt lake lithium deposits in the country have not been developed and utilized. Therefore, breakthroughs in salt lake lithium extraction technology will greatly increase the supply of China's salt lake lithium resources. It is believed that the innovation of brine lithium extraction technology will change the supply pattern of lithium products and the international trade ecology. The release of China's brine-type lithium mine production capacity may become the main growth pole in the future, thereby reducing the country's dependence on foreign lithium resources.

The development technology of lithium in controlled nuclear fusion will become a new technology that countries are competing to develop and is highly confidential. The maturity and widespread use of this technology in the future will greatly change the way people live, especially the way new energy is used in the future. By then, severely polluted coal mines may be permanently closed. The problem of insufficient natural gas will also be solved. With the help of lithium controlled nuclear fusion, an economical, environmentally friendly and long-lasting new energy source, space travel may become a commonplace in people's daily life.

The recycling and utilization of lithium batteries will become an emerging industry. In the future, the lives and even survival of more people will be closely related to this industry.

The international trade futures market for lithium products will become more and more prosperous. Accordingly, the formulation of global international trade rules and conventions for lithium products will soon be on the agenda. Countries that actively participate, or even promptly initiate and participate in the formulation of relevant international trade rules will have the right to speak and bargain in the corresponding trade negotiations, and even become the leaders and controllers in this regard.

At present, China, Japan, and South Korea are the largest regions for lithium product consumption in the world, while Australia and Chile in South America are important lithium product suppliers. If these countries unite to initiate relevant multilateral trade agreements and conduct trade negotiations on the import and export of lithium products, they will definitely occupy the commanding heights of bargaining power in the future global lithium product trade and improve the international competitiveness of their respective lithium product-related companies.

Obviously, lithium resources will have an increasingly close relationship with the financial system. Whoever takes the lead in this regard may become an emerging capital power or even an emerging hegemon in the future.

In fact, some countries with strategic vision have consciously deployed and controlled overseas high-quality lithium resources with the help of relevant domestic institutions and enterprises. They use investment and mergers and acquisitions to target high-quality potential areas with rich lithium resources but not yet developed on a large scale, select overseas lithium deposits with lithium resource advantages and relatively mature exploration, plan and layout in advance, and strengthen international mining investment and development cooperation, so as to maximize the use of overseas lithium products.

8 Conclusions

Lithium's natural genes, that is, its chemical properties, determine its widespread use in many fields today, especially in related fields such as electronic products and electric vehicles. This has also triggered a global boom in its search, exploration and development, and has led to the worship and pursuit of it by the capital world.

We believe that in the near future, international rules and regulations on lithium product trade will definitely be released and regulate people's related trade in this product. At the same time, lithium resources and related products may assume some of the functions of international currencies, just like gold. The country that has more lithium mineral resources and related products will have the international pricing power of lithium products, and even have the right to speak in other international affairs. In other words, lithium resources and products may change a country's national destiny and world status to a certain extent.

The lithium futures and auction pricing models that have emerged in recent years will not only continue to impact the traditional mainstream long-term contract pricing model, but will also become more prosperous and have the potential to replace the traditional pricing model. It should be noted that the new pricing model may intensify the supply and demand tension and continue to push up the price of lithium products.

In the foreseeable future, the global supply and demand of lithium products will continue to grow rapidly. Australia, Chile, and Argentina will continue to be the main suppliers of lithium products in the world in the next few decades. The four countries once accounted for more than 95% of the global share. This situation will continue for a long time. China, Japan and South Korea were once the main demand sides of lithium products, accounting for more than 70% of the three countries. In the future, this trend will fluctuate due to international political games, but there will be no fundamental changes.

At the same time, driven by policies, markets and environment, the global new energy industry will continue to flourish. In response to this, the investment in lithium exploration funds will continue to grow, and the transaction of lithium mining rights will also be very prosperous, especially in underdeveloped regions such as Africa, South America and Eastern Europe. Because so far, many countries in these regions have not raised lithium resources to a strict national strategic level.

With the turmoil and changes in international politics, China's situation as the world's largest lithium product consumer and trading country will change, and the situation of insufficient domestic lithium resource supply and high external dependence will also change accordingly. However, the country's low level of development of brine-type lithium deposits, imperfect industrial chain structure of lithium resource market, lagging construction of lithium futures market and related financial system, and weak international competitiveness of related enterprises and financial institutions will still exist.

Lithium will occupy an increasingly important position in the new generation of clean and efficient energy metals, and will attract more and more people's attention.

9 References

1. https://ir.sqm.com/English/news/news-details/2024/SQM-and-Codelco-Sign-Partnership-Agreement/default.aspx. Retrieved June 2, 2024.

2. Yin JZ, Yin HY, Chao YH & Shi HY. 2024d. Energy and lithium deposits. *AIMS Geosciences*, 10 (1): 28-42. DOI: 10.3934/geosci.2024002.

3. Prohaska T, Irrgeher J, Benefield J, Böhlke JK, Chesson LA, Coplen TB, Ding TP, Dunn PJH, Gröning M, Holden NE & Harro AJ. 2022. Standard atomic weights of the elements 2021 (IUPAC Technical Report). *Pure and Applied Chemistry*. DOI: 10.1515/pac-2019-0603.

4. Dye JL. (1977). J. *Chem.Educ*., 54 (6): 332.

5. Liu YL & Ren DH. 1984. Inorganic Chemistry Series, Vol. 1. Beijing: Science Press, pp 289-354.

6. Kamienski CW, McDonald DP, Stark MW & Papcun JR. 2004. Lithium and lithium compounds. *Kirk-Othmer Encyclopedia of Chemical Technology*. John Wiley & Sons, Inc. ISBN 978-0471238966. DOI:10.1002/0471238961.1209200811011309.a01.pub2.

7. Boesgaard AM & Steigman G. 1985. Big bang nucleosynthesis - Theories and observations. *Annual Review of Astronomy and Astrophysics (Palo Alto, CA)*, 23: 319–378. DOI: 10.1146/annurev.aa.23.090185.001535. A86-14507 04-90.

8. Indra O. 2019. The geopolitics of renewable energy: Debunking four emerging myths. *Energy Research & Social Science*, 49: 36–40. DOI: 10.1016/j.erss.2018.10.018.

9. Atkins Peter. 2010. *Shriver & Atkins' Inorganic Chemistry 5th*. New York: W. H. Freeman and Company. 296.

10. Taylor SR & McLennan SM. 1985. *The continental crust: Its composition and evolution*. Blackwell Sci. Publ., Oxford, 330 pp.

11. Garrett D. 2004. *Handbook of Lithium and Natural Calcium Chloride*. Elsevier Academic Press, 488 pp.

12. Czech Geological Survey. 2015. *Mineral Commodity Summaries of the Czech Republic 2015 (PDF)*. Prague: Czech Geological Survey. 373. ISBN 978-80-7075-904-2. p.373.

13. Xue YY, Liu HY & Sun WD. 2021. Geochemical properties and enrichment mechanism of lithium. *Geotectonics and Mineralization*, 45 (6): 1202-1215.

14. Clark J. 2009. *Compounds of the Group 1 Elements*.

15. Weeks M. *Discovery of the Elements*. Whitefish, Montana, United States: Kessinger Publishing. 2003: 124.

16. Krebs RE. 2006. *The History and Use of Our Earth's Chemical Elements: A Reference Guide*. Westport Conn.: Greenwood Press.

17. Garrett D. 2004. *Handbook of lithium and natural calcium chloride: Their deposits, processing, uses and properties*. Elsevier Academic Press: 651.

18. Enghag P. 2004. Encyclopedia of the Elements: Technical Data-History-Processing-Applications. Wiley: 287–300.

19. Emsley J. 2001. *Nature's Building Blocks*. Oxford: Oxford University Press. ISBN 978-0-19-850341-5.

20. Timeline science and engineering. 2008. *Dirac Delta Science & Engineering Encyclopedia*.

21. Green T. 2006. Analysis of the Element Lithium. *echeat*.

22. Overhauser AW. 1984. Crystal structure of lithium at 4.2 K. *Physical Review Letters*, 53 (1): 64–65. DOI:10.1103/PhysRevLett.53.64.

23. Seitz HM, Brey GP, Lahaye Y, Durali S & Weyer S. 2004. Lithium isotopic signatures of peridotite xenoliths and isotopic fractionation at high temperature between olivine and pyroxenes. *Chemical Geology*, 212 (1–2): 163–177. DOI:10.1016/j.chemgeo.2004.08.009.

24. Duarte FJ. 2009. *Tunable Laser Applications*. CRC Press: 330.

25. Wikipedia. 2023. *Lithium*. Available from: https://en.wikipedia.org/wiki/Lithium.

26. Evans RK. March and July 2008. *An Abundance of Lithium: Part one and Part Two*.

27. Huang CF & Kresin VV. 2016. Note: Contamination-free loading of lithium metal into a nozzle source. *Review of Scientific Instruments*. 87 (6): 066105. Bibcode: 2016RScI...87f6105H. DOI: 10.1063/1.4953918.

28. Xing K, Zhu Q, Ren JP, Zhou XH, Niu ML, Liu JA & Xiao Y. 2023. Research on the characteristics and market development trend of global lithium resources. *Geological Bulletin of China*, 42 (8): 1402-1421. DOI: 10.12097/j.issn.1671-2552.2023.08.012.

29. Tuoriniemi J, Juntunen-Nurmilaukas K, Uusvuori J, Pentti E, Salmela A & Sebedash A. 2007. Superconductivity in lithium below 0.4 millikelvins at ambient pressure. *Nature*, 447 (7141): 187–189.

30. Struzhkin VV, Eremets MI, Gan W, Mao HK & Hemley RJ. 2002. Superconductivity in dense lithium. *Science*, 298 (5596): 1213–1215.

31. Schwarz U. 2004. Metallic high-pressure modifications of main group elements. *Zeitschrift für Kristallographie*, 219: 376–390. DOI:10.1524/zkri.219.6.376.34637. S2CID 56006683.

32. Meija J. 2016. Atomic weights of the elements. 2013. IUPAC Technical Report. *Pure and Applied Chemistry*, 88 (3): 265–291. DOI: 10.1515/pac-2015-0305.

33. Kondev FG, Wang M, Huang WJ, Naimi S & Audi G. 2021. The NUBASE 2020 evaluation of nuclear properties. *Chinese Physics C*. 45 (3): 030001. DOI:10.1088/1674-1137/abddae.

34. USGS. *Mineral Commodity Summaries (2011-2022)*. 2022. http://minerals.usgs.gov/minerals/pubs/mcs/2011-2022.pdf.

35. Benson TR, Coble MA, Rytuba JJ & Mahood, GA. 2017. Lithium enrichment in intercontinental rhyolite magmas leads to Li deposits in Caldera basins. *Nat Commun*, 8, 270. DOI: https://doi.org/10.1038/s41467-017-00234-y.

36. Zhai MG, Wu FY, Hu RZ, Jiang SY, Li WC, Wang RC, Wang DH, Qi T, Qin KZ & Wen HJ. 2019. Strategic critical metal mineral resources: current status and problems. *Chinese Science Foundation*, 33 (2): 106-111.

37. Moores S. 2007. Between a rock and a salt lake. *Industrial Minerals*, 477: 58.

38. Wu XS, Sun Y, Wang DH, Huang WB, Huang F, Gao X, Zhang W & Yao X. 2020. International

Technical Status, Innovation and Prospect of Lithium Mineral Development. *Comprehensive Utilization of Mineral Resources*, (6): 115-125.

39. Risen J. U.S. Identifies Vast Riches of Minerals in Afghanistan. *The New York Times*. 13 June 2010.

40. Wang GS & Li JX. 2021. *Global lithium, cobalt, nickel, tin and potash mineral reserve assessment report*. Global Mineral Resources Strategic Research Center, China Geological Survey.

41. Benson TR, Matthew AC & Dilless JH. 2023. Hydrothermal enrichment of lithium in intracaldera illite-bearing claystones. *Science Advances,* 9 (35). DOI: 10.1126/sciadv.adh8183.

42. Kesler SE, Gruber PW & Medina PA. 2012. Global lithium resources: Relative importance of pegmatite, brine and other deposits. *Ore Geology Review*, 48: 55-69. DOI: 10.1016/j.oregeorev.2012.05.006.

43. Mohr SH, Mudd GM & Giurco D. Lithium resources and production: critical assessment and global projections. *Minerals*, 2012, 2: 65-84. DOI: 10.3969/j.issn.1006-5296.2012.02.001.

44. Vikström H, Davidsson S & Höök M. 2013. Lithium availability and future production outlooks. *Applied Energy*, 110 (10): 252-266.

45. Cai YL & Li JW. 2017. Analysis and enlightenment of global lithium resource, development and utilization situation. *Acta Geoscientia Sinica*, 38 (1): 25-29. https://www.cnki.com.cn/Article/CJFDTOTAL-DQXB201701005.htm.

46. Cao TY. 2011. Japan's rare metal security strategy. *Land and Resources Information*, (4): 42-46. https://www.cnki.com.cn/Article/CJFDTOTAL-GTZQ201104011.htm.

47. Chen JB & Yu LH. 2020. *Comparative analysis of mineral resource situation in China, the United States and Europe*. Beijing: Geological Publishing House.

48. Guan YL & Chai WS. Lithium market development trends under the background of global carbon neutrality. 2021. *Comprehensive Utilization of Resources in China*, 39 (7): 92-96. https://www.cnki.com.cn/Article/CJFDTOTAL-ZWZS202107028.htm.

49. He JX, Cui RG & Liu Wei. 2020. Development and prospects of global lithium mining industry. *Land and Resources Information*, 4 (10): 21-26. https://www.cnki.com.cn/Article/CJFDTOTAL-GTZQ202010004.htm.

50. Wang QS & Yuan CH. 2019. Global lithium supply situation and suggestions for my country's resource security. *China Mining*, 28 (5): 1-6. https://www.cnki.com.cn/Article/CJFDTOTAL-ZGKA201905001.htm.

51. Wu XS, Sun Y & Wang DH. 2020. The technical status, innovation and prospects of international lithium mine development. *Comprehensive Utilization of Mineral Resources*, 6: 110-120. https://www.cnki.com.cn/Article/CJFDTOTAL-KCZL202006019.htm.

52. Xia P, Ren SM & Zhou XH. 2022. *Global Mining Development Report 2020-2021*. Beijing: Geological Publishing House.

53. Yang HP, Liu L & Ding GF. 2019. Current status and development trend of global lithium mineral resources. *Mineral Conservation and Utilization*, 9 (5): 26-40. https://www.cnki.com.cn/Article/CJFDTOTAL-KCBH201905004.htm.

54. Chen QS, Zhang YF & Xing JY. 2021. Theory and methods of strategic mineral determination at home and abroad. *Acta Geoscientia Sinica*, 42 (2): 137-144. https://www.cnki.com.cn/Article/CJFDTOTAL-DQXB202102002.htm.

55. Kudryavtsev P. 2016. Lithium in nature, application, methods of extraction (review). *Scientific Israel: Technological Advantages*, 18 (3): 63-83.

56. Ding T, Zheng MP & Zhang XF. 2020. Lithium extraction technology and industrial development from salt lake brine. *Science and Technology Review*, 38 (15): 16-23. https://www.cnki.com.cn/Article/CJFDTOTAL-KJDB202015004.htm.

57. Chen HX, Yan H, Sun YL & Ma GQ. 2024. Research progress in lithium resource extraction technology. *Inorganic Salt Industry*, (1): 9-22.

58. Tan MC, Liang YJ, Li QZ, Ke Y, Peng C, Zhu ZH, Bai BW & Chai LY. 2024. Analysis on the development of key nonferrous metal extraction and recovery technology for new energy vehicles. *Modern Transportation and Metallurgical Material*, (1): 3-10.

59. Yang YS, Yao ZH, Zhao ZX, Feng X, Zeng Y, Yu XD. 2024. Progress in experimental research on evaporation of lithium-rich sulfate salt lake brine. *Inorganic Salt Industry*，(4): 1-7.

60. Ma SQ, Li CW, Wang QH, Chen XL, Qin Y & Shi CL. 2024. Kinetic study on the extraction of lithium from salt lake brine using bisimidazolium ionic liquid system. *Qinghai Science and Technology*, (01): 116-121+129 .

61. Su H, Zhu ZW & Wang LN. Research progress in extraction and recovery of lithium from ore resources. 2019. *Journal of Chemical Industry and Engineering*, 70 (1): 10-23. https://www.cnki.com.cn/Article/CJFDTOTAL-HGSZ201901002.htm.

62. Schwochau Klaus. 1984. Extraction of metals from sea water. *Inorganic Chemistry*. Topics in Current Chemistry 124. Springer Berlin Heidelberg: 91–133. DOI:10.1007/3-540-13534-0_3.

63. Schulz KJ, DeYoung JH & Jr. Seal RR II. 2017. Critical mineral resources of the United States-Economic and environmental geology and prospects for future supply. *U.S. Geological Survey Professional Paper*, 1802: 1-21.

64. Ma Z & Li JW. 2018. Research on China's lithium resource supply system: current situation, problems and suggestions. *China Mining*, 27 (10): 1-7. https://www.cnki.com.cn/Article/CJFDTOTAL-ZGKA201810001.htm.

65. Jiang W, Liu TC, Li W, Pei SL & Du B. 2023. The rapid growth of China's new energy vehicle market and its challenges to lithium resources. *Mineral Exploration*, (10): 1814-1824.

66. Zhang SJ, Zhang YW, Zhang LW, Jiang AL & Liu GY. 2020. The current status of China's lithium mineral resources and its sustainable development strategy. *Inorganic Salt Industry*, 52 (7).

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.

Original Article

The evolution of climate science: past, present, and future

You-Zhi Tang[1] ©

Abstract

This article reviews the evolution of the climate science, including its history, current status and development trends expected. Having the interdisciplinary nature dedicated to studying the climate system, including its components, processes, and interactions, climate science is relatively a new field of science but with its foundational concepts laid in the 19th century. Its development into a distinct and mature field took place primarily in the 20th century, especially in response to the growing recognition of human impacts on the climate. It encompasses the examination of long-term patterns and changes in temperature, precipitation, and other atmospheric conditions to understand and predict the behavior of Earth's climate. This field of science integrates knowledge from various disciplines, including but not limited to, meteorology, oceanography, geology, physics, chemistry, biology, and environmental science, to provide a comprehensive understanding of the climate system and its impacts. It aims to improve our comprehension of climate variability and change, and enhance predictive capabilities. Today, climate science is a vital area of research, evolving from rudimentary observations to empirical extrapolations or speculative predictions, further to a sophisticated understanding of Earth's climate systems. It enables informing policies and strategies for addressing climate change, particularly for managing and mitigating the effects of climate change. With ongoing advancements in technology and methodology, particularly in achievements in artificial intelligence, climate science is poised to continue its critical role in addressing the challenges of climate change. As we move forward, interdisciplinary collaboration, improved observational capabilities, more accurate predictions, effective communication, and more powerful mitigation measures will be essential in guiding global efforts to mitigate and adapt to the impacts of a changing climate.

Key words: climate science; history; status; future trend; global warming; climate change and crisis

---

Affiliation Info: [1] Independent Researcher, Suite M713, 2 Sun Yat Sen Avenue, Markham, Ontario, Canada, L3R 5Z3

Article Info: Received: 6 September, 2024 / Revised: 13 October 2024 / Accepted: 26 October 2024 / Published Online: 18 November 2024. www.naturalisscientias.com

Authors' Contact Info: Tang, YZ: yztang@rogers.com

Citation: YZ Tang. 2024. The evolution of climate science: past, present, and future. *Naturalis Scientias*, 1 (3): 218-227. DOI: https://doi.org/10.62252/NSS.2024.1016.

Corresponding Aurhor©: YZ Tang; PhD; Email: yztang@rogers.com

1 Introduction

Climate science is relatively a new field of science having the interdisciplinary nature dedicated to studying the climate system, including its components, processes, and interactions. While having roots that extend back centuries, it has developed significantly as a distinct field primarily in the 20th and 21st centuries with its foundational concepts laid in the 19th century. Its development into a distinct and mature field took place primarily in the 20th century, especially in response to the growing recognition of human impacts on the climate. It encompasses the examination of long-term patterns and changes in temperature, precipitation, and other atmospheric conditions to understand and predict the behavior of Earth's climate.

This field of science integrates knowledge from various disciplines, including but not limited to, meteorology, oceanography, geology, physics, chemistry, biology, and environmental science, to provide a comprehensive understanding of the climate system and its impacts. It aims to improve our comprehension of climate variability and change, and enhance predictive capabilities. Today, climate science is a vital area of research, informing policies and strategies for addressing climate change, particularly for managing and mitigating the effects of climate change.

Overall, climate science has undergone a profound transformation over the past century, evolving from rudimentary observations to empirical extrapolations or speculative predictions, further to a sophisticated understanding of Earth's climate systems. This evolution reflects advancements in technology, methodology, and scientific inquiry. Understanding the past developments and current status of climate science is crucial for addressing future challenges related to climate change.

2 Early foundations

The roots of climate science can be traced back to the late 18th and early 19th centuries, during the Enlightenment, when scientists began systematically studying the Earth's atmosphere. One of the early milestones was Joseph Fourier's recognition in the 1820s of the greenhouse effect, a process by which the Earth's atmosphere traps heat, making the planet warmer than it would be without an atmosphere. Fourier's work laid the foundation for future investigations into how atmospheric gases affect the Earth's temperature. His paper was published in the Memoirs of the Royal Academy of Sciences, where he suggested the idea that there would be higher temperatures on Earth due to the “greenhouse effect”, compared to what would be expected if there were no atmosphere[1].

In the mid-19th century, John Tyndall, an Irish physicist, identified specific gases, such as water vapor, carbon dioxide (CO_2), and methane, as significant contributors to the greenhouse effect, by trapping heat in the atmosphere similar to the glass of a greenhouse built for planting[2]. His experiments demonstrated that these gases absorb infrared radiation, leading to the warming of the atmosphere. Svante Arrhenius, a Swedish scientist, took this research further in 1896 by quantifying the relationship between CO_2 concentrations and global temperatures, providing an early model for understanding anthropogenic climate change[3].

However, by that time much of the scientific work related to climate was based on empirical observations. Both Tyndall and Arrhenius used empirical data to understand the behavior of gases in the atmosphere and to estimate their impact on Earth's temperature. Arrhenius made calculations based on the known properties of carbon dioxide and its effect on the Earth's energy balance to predict the impact of increased CO_2 levels on global temperatures. He was the first to suggest that human activities, such as burning fossil fuels, could lead to global warming - a theory that has since been validated by extensive research.

Predictions in the 19th century were less sophisticated compared to modern climate science due to the limited availability of data and computational tools. However, they were still significant. Arrhenius, for example, used his understanding of the greenhouse effect to predict that doubling the concentration of CO_2 in the atmosphere could lead to a significant increase in Earth's temperature. While these predictions were based on empirical data, they involved a level of theoretical extrapolation and mathematical modeling.

Nowadays, it is generally understood that the greenhouse effect is a natural process that warms Earth's surface. It occurs when certain gases in Earth's atmosphere trap heat, preventing it from escaping into space. These gases are known as greenhouse gases (GHGs) and include carbon dioxide (CO_2), methane (CH_4), water vapor (H_2O), and nitrous oxide (N_2O).

Here is a brief description on how the greenhouse effect works:

- **Solar radiation**: The Sun emits energy in the form of solar radiation. When this radiation reaches Earth, some of it is absorbed by the surface, warming it.
- **Infrared radiation**: The Earth's surface, now warmed, emits energy back towards the atmosphere as infrared radiation (heat).
- **Absorption by greenhouse gases**: Greenhouse gases in the atmosphere absorb some of this infrared radiation. Instead of letting it escape into space, these gases re-radiate the heat in all directions, including back towards the Earth's surface.
- **Heat retention**: This process effectively traps heat within the atmosphere, warming the lower atmosphere and the Earth's surface.
- **Balance**: In a stable climate, the amount of energy coming from the Sun is balanced by the amount of energy leaving the Earth. However, increased concentrations of greenhouse gases enhance this effect, leading to more heat being trapped on the earth and thus contributing to global warming.

Figure 1 is an illustration on how the greenhouse effect works.

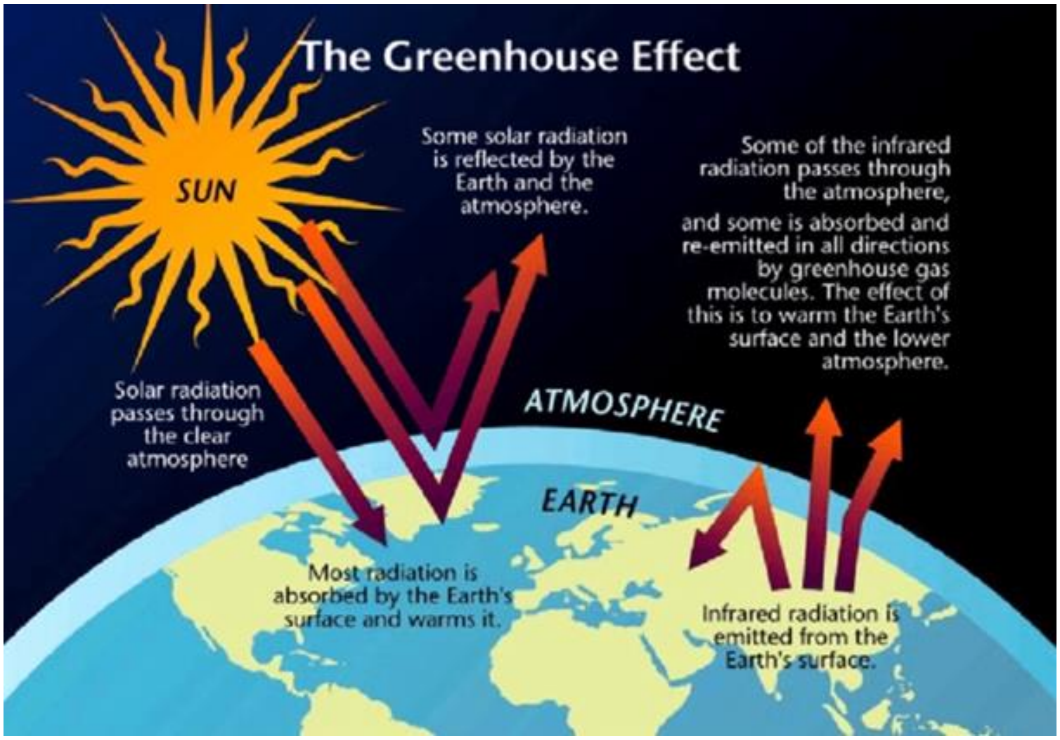


Figure 1. Illustration of the greenhouse effect[4]

3 The rise of modern climate science

The 20th century marked rapid expansion in climate science, driven by advancements in technology and computing enabling more sophisticated observations and models, thus an increased understanding of atmospheric dynamics. The development of global temperature records, starting in the early 20th century, allowed scientists to identify trends and anomalies in the Earth's climate. The 1950s and 1960s saw the emergence of atmospheric CO_2 monitoring, most notably through the Keeling Curve[5], which provided clear evidence of rising CO_2 levels due to human activities (Figure 2).

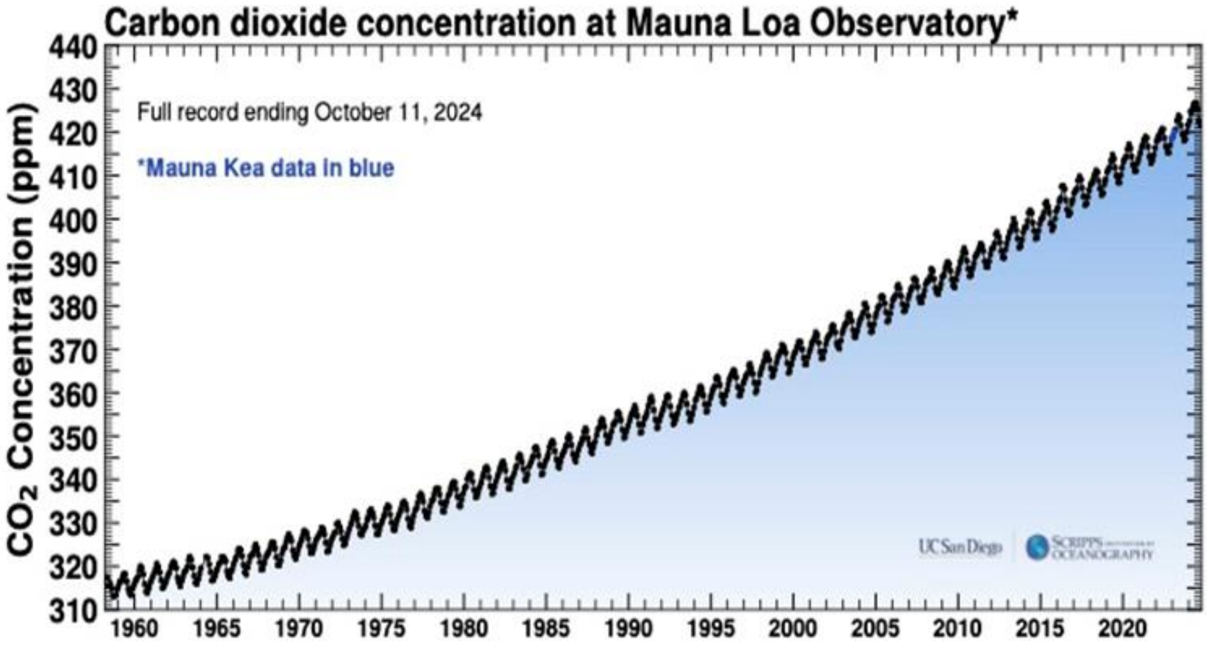


Figure 2. Increase in carbon dioxide level in the atmosphere[6]

The development of numerical weather prediction models in the 1950s allowed scientists to simulate climate conditions, understand the complexities of the Earth's climate system and predict future scenarios. This period also witnessed the establishment of key institutions and programs, such as the Intergovernmental Panel on Climate Change (IPCC), founded in 1988 to assess scientific knowledge and inform policy[7]. It provided a forum for scientists to assess and communicate the risks associated with climate change. The IPCC's assessment reports have since become the cornerstone of global climate policy discussions.

Satellite technology, which became prominent in the 1970s, revolutionized climate observation by providing comprehensive data on atmospheric temperatures, sea levels, and ice cover. This technology has been instrumental in monitoring changes in Earth's climate system and validating climate models[8].

In summary, modern climate science focuses on the following four major aspects, using interdisciplinary approaches:

- **Components and processes**: Climate science investigates the various elements of the climate system—such as the atmosphere, oceans, land surfaces, and ice masses—and how they interact. This includes studying atmospheric dynamics, ocean currents, heat exchanges, and feedback mechanisms that influence climate patterns.
- **Historical and modern data**: It involves analyzing historical climate data to identify trends and variability, as well as using modern observational tools like satellites, weather stations, and climate models to gather current and predictive information.
- **Climate models**: Scientists use computer models to simulate and predict climate behavior under different scenarios. These models help in understanding how changes in greenhouse gas concentrations, land use, and other factors can affect future climate conditions.
- **Impacts and adaptation**: Climate science also explores the impacts of climate change on ecosystems, human societies, and economies. This includes studying phenomena like extreme weather events, sea-level rise, and changes in biodiversity, as well as developing strategies for adaptation and mitigation.

4 Current status of climate science and the climate

Today, climate science is a robust field characterized by advanced computational models, extensive datasets, and a high level of scientific consensus on climate change. The key findings of recent assessments, such as the IPCC's Sixth Assessment Report (AR6), highlight several critical aspects of current climate understanding:

- **Global warming trends**: Average global temperatures have risen significantly, with 2020 being one of the hottest years on record. The past decade has been the warmest in the historical record[7].
- **Attribution of climate change**: There is a high level of confidence that human activities, particularly the burning of fossil fuels and deforestation, are the primary drivers of recent global warming. The IPCC AR6 report states that it is "unequivocal" that human influence has warmed the atmosphere, oceans, and land[7].
- **Impact projections**: Future projections indicate more frequent and severe heat waves, rising sea levels, and increased intensity of extreme weather events. These impacts are expected to have profound effects on ecosystems, human health, and economies[7].
- **Mitigation and adaptation**: There is an ongoing focus on strategies to mitigate climate change by reducing greenhouse gas emissions and adapting to its unavoidable impacts. Efforts include transitioning to renewable energy sources, enhancing energy efficiency, and developing adaptive infrastructure[9].

The Intergovernmental Panel on Climate Change (IPCC) reports provide a comprehensive and scientifically rigorous assessment of the current state of the Earth's climate and the challenges posed by global warming. The IPCC's AR6 Synthesis Report (SYR) as a comprehensive and authoritative document integrates the findings from the three Working Groups of the Sixth Assessment Report. It provides a clear, scientifically grounded overview of the current state of the climate, the risks and impacts associated with climate change, and the necessary pathways to address these challenges[10].

4.1 Current status of our climate and global warming

Warming trends: The Earth's surface temperature has increased by approximately 1.1 °C above pre-industrial levels (1850-1900) due to human activities, primarily the burning of fossil fuels and deforestation as shown in Figure 3.

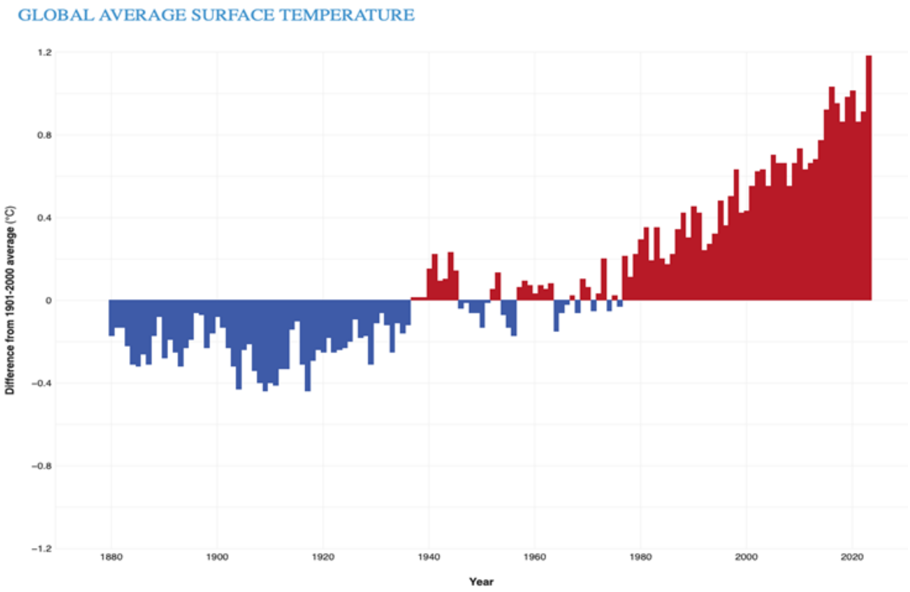


Figure 3. Warming trend of the Earth’s surface[11]

The last few decades have been the warmest on record, with each of the past four decades successively warmer than any decade that preceded it since 1850.

It is reaffirmed that human activities, particularly the burning of fossil fuels and deforestation, are unequivocally responsible for the observed warming of the climate system.

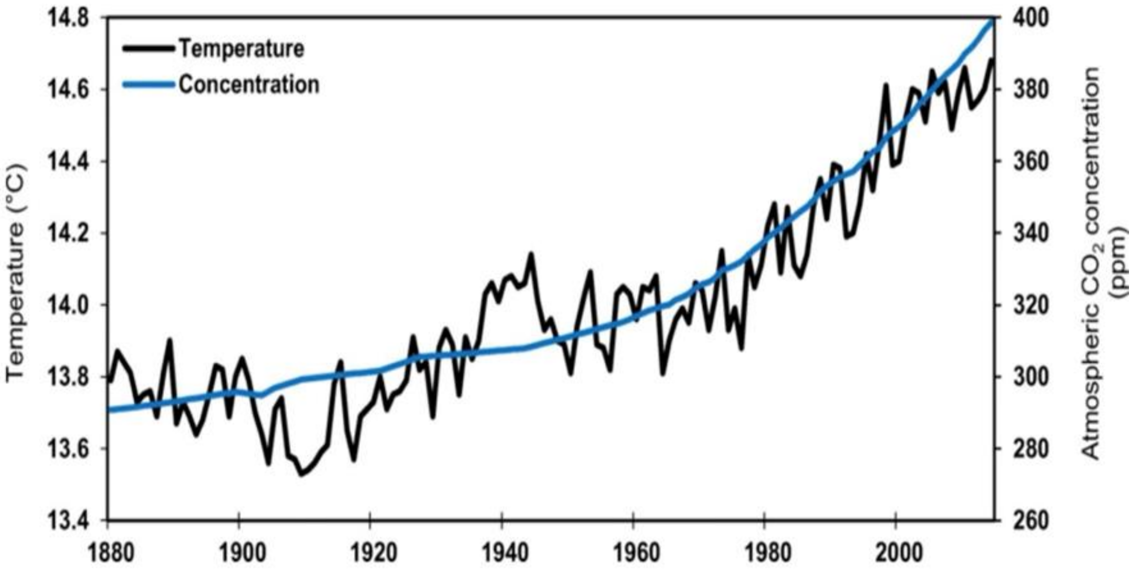
It is emphasized that the scale of recent changes across the climate system is unprecedented over many centuries to millennia.

Greenhouse gas concentrations: Concentrations of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are at unprecedented levels in at least the last 800,000 years.

CO_2 levels have increased by about 50% since the pre-industrial era.

Clearly the rising global temperature is correlated well with the increase in CO_2 concentration as shown in Figure 4.

It is urgently needed for immediate and deep reductions in greenhouse gas (GHG) emissions to avoid the most severe impacts of climate change.



Average global temperature and atmospheric CO2 concentration, 1880-2014. Source: the authors based on data from the Earth Policy Institute (2017)

Figure 4. Correlation between carbon dioxide concentration and global warming[12]

Impacts on the climate system: Climate change is already affecting every region on Earth, with impacts becoming more frequent, severe and widespread.

These include more frequent and intense heat waves, storms, and extreme precipitation events, as well as other extreme weather phenomena.

Glaciers and ice sheets are melting, contributing to rising sea levels, which threaten coastal communities and ecosystems.

Ocean temperatures are rising, leading to increased ocean acidification and deoxygenation, affecting marine life.

The impacts are disproportionately affecting vulnerable populations, particularly in low-income countries and marginalized communities.

Irreversible Changes: Some aspects of climate change, such as sea level rise and the loss of polar ice, are irreversible over centuries to millennia.

Continued warming will exacerbate these impacts, leading to long-lasting consequences for ecosystems and human societies.

Even if we stopped emitting GHGs today, certain impacts would continue to unfold.

The window of opportunity to limit global warming to 1.5 °C above pre-industrial levels is rapidly closing, and current global efforts are insufficient to meet this target. temperature.

4.2 Current status of our climate and global warming

Mitigation of emissions: To limit global warming to 1.5 °C or 2 °C above pre-industrial levels, as outlined in the Paris Agreement, the world needs to achieve significant reductions in GHG emissions. Current policies and pledges are not sufficient to meet these targets, leading to concerns about exceeding these thresholds.

Adaptation to impacts: Even with significant mitigation efforts, some degree of climate change is inevitable. Communities worldwide must adapt to the impacts of climate change, such as rising sea levels, increased frequency of extreme weather events, and shifts in agricultural productivity. However, adaptation is challenging, especially for vulnerable populations with limited resources.

Economic and social disruption: Climate change poses significant risks to economies, infrastructure, and human health. Extreme weather events can disrupt food and water supplies, displace populations, and exacerbate poverty and inequality. The economic costs of inaction are expected to be far higher than the costs of taking preventive measures.

Loss of biodiversity: The changing climate is leading to shifts in ecosystems and the loss of biodiversity. Species that cannot adapt or migrate to new habitats face extinction, which can have cascading effects on ecosystems and human livelihoods.

Political and social will: Addressing climate change requires global cooperation and strong political will. However, climate action is often hindered by political divisions, economic interests, and public skepticism. Achieving the necessary scale of change requires not only technological advancements but also societal transformation.

4.3 Potential solutions to address these challenges

Transition to renewable energy: A rapid transition from fossil fuels to renewable energy sources such as solar, wind, and hydropower is essential. This transition includes scaling up clean energy technologies, improving energy efficiency, and investing in energy storage solutions.

Carbon pricing and regulation: Implementing carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, can incentivize reductions in GHG emissions. Strong regulatory frameworks that limit emissions from key sectors like energy, transportation, and industry are also crucial.

Nature-based solutions: Protecting and restoring natural ecosystems, such as forests, wetlands, and mangroves, can enhance carbon sequestration, reduce climate risks, and support biodiversity. Sustainable land management practices and reforestation efforts are vital components of these solutions.

Climate adaptation and resilience: Investing in infrastructure that can withstand extreme weather, improving water management systems, and developing early warning systems for natural disasters are key adaptation strategies. Building resilience also involves supporting vulnerable communities and integrating climate risks into urban planning.

Technological innovation: Advancements in technology, including carbon capture, utilization and storage (CCUS), renewable energy innovations, and climate-resilient agricultural practices, can play a significant role in mitigating and adapting to climate change. Research and development in these areas need to be accelerated.

Global cooperation and governance: International collaboration is critical for addressing climate change. Strengthening global agreements, such as the Paris Agreement, and ensuring that countries meet their commitments is essential. Enhanced support for developing countries, including financial and technical assistance, is also necessary.

Public awareness and education: Raising public awareness about climate change and its impacts can drive behavioral changes and build support for climate policies. Education and community engagement are key to fostering a culture of sustainability and empowering individuals to take action.

In conclusion, the IPCC reports paint a clear picture of the urgent need for action to address the global climate crisis. While the challenges are immense, the solutions are within reach if we act decisively and collectively. A combination of technological innovation, policy measures, nature-based solutions, and global cooperation can help mitigate the worst impacts of climate change and build a more sustainable and resilient future.

5 Future trends in climate science

Today, climate science is a robust field characterized by advanced computational models, extensive datasets, and a

Looking ahead, several trends are likely to shape the future of climate science:

Enhanced climate models: Advances in computing power and data assimilation techniques will continue to improve the accuracy of climate models. The integration of artificial intelligence and machine learning is expected to enhance predictive capabilities and allow for more detailed regional forecasts[13].

Improved observational networks: Expansion of satellite and ground-based observational networks will provide more granular data on climate variables. This will improve our understanding of regional climate dynamics and enhance early warning systems for extreme weather events[14].

Interdisciplinary research: Future climate science will increasingly rely on interdisciplinary approaches, integrating insights from fields such as ecology, economics, and social sciences. This holistic perspective will be crucial for developing comprehensive strategies to address climate impacts and inform policy decisions[15].

Public engagement and policy: Effective communication of climate science to the public and policymakers will be vital in driving action. Enhanced transparency and engagement efforts will help bridge the gap between scientific research and policy implementation[16].

Climate change adaptation and mitigation technologies and engineering.

Artificial intelligence: In addition to enhance climate models mentioned above, AI is revolutionizing climate science by also enhancing our ability to predict and respond to climate change. It enables more accurate and localized predictions, improves the management of big data, and supports the development of effective mitigation and adaptation strategies. However, the integration of AI into climate science also requires careful consideration of ethical, environmental, and interdisciplinary challenges. Overall, AI holds significant promise in advancing our understanding and response to the global climate crisis.

6 Discussion

Evolution and advancement of any subject of science takes its natural course and is often accelerated by the realities and particularly by urgent challenges confronted by mankind. Climate science is no exception. Into the 20th and 21st centuries, impacts of climate change to human society became more and more obvious and serious, and this subject has attracted more and more public attention which helped to build political will in response to the increasing pressure from the society and internationally. Thus, studies on the climate are getting flourishing, and new innovations and advanced technologies have brought more breakthrough discoveries. Access to increased fundings and resources, interdisciplinary collaboration, global cooperation, international initiatives, and open-source knowledge sharing, all contributed to the rapid development of climate science in the recent decades. As the application of AI becomes widespread, the advancement of this field will definitely accelerate, and become more precise and accurate.

7 Conclusions

The evolution of climate science reflects a journey from early theoretical insights to a sophisticated understanding of Earth's climate system. With ongoing advancements in technology and methodology, climate science is poised to continue its critical role in addressing the challenges of climate change. As we move forward, interdisciplinary collaboration, improved observational capabilities, more accurate predictions, effective communication, and more powerful mitigation measures will be essential in guiding and facilitating global efforts to mitigate and adapt to the impacts of a changing climate. The urgence for action to address the global climate crisis is also obvious. It is expected that AI would play an increasing role in climate science.

Acknowledgements: Special thanks to the editor and reviewers of Naturalis Scientias for their comments and suggestions.

8 References

1. Fourier J. 1827. Mémoire sur les températures du globe terrestre et des espaces planétaires. Mémoires de l'Académie. *Royale des Sciences de l'Institut de France*, 7: 569-604.
2. Tyndall J. 1861. On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absorption, and conduction. *Philosophical Transactions of the Royal Society of London*, 151: 1-36.
3. Arrhenius S. 1896. On the influence of carbonic acid in the air upon the temperature of the ground. *Philosophical Magazine*, 41: 237-276.
4. Schuler J. Researchgate.net. 2024, https://www.researchgate.net/figure/The-Greenhouse-Effect_fig1_237730165. Retrieved October 19, 2024.
5. Keeling CD, Piper SC, Bacastow RB, Wahlen M, Whorf TP, Heimann M and Meijer HA. 2005. Atmospheric CO_2 and $^{13}C_{CO2}$ exchange with the terrestrial biosphere and oceans from 1978 to 2000: observations and carbon cycle implications. In: Ehleringer JR, Cerling TE and Dearing MD (eds). *A History of Atmospheric* CO_2 *and its effects on Plants, Animals, and Ecosystems*, New York: Springer Verlag, 83-113.
6. Scripps Institution of Oceanography at UC San Diego. 2024. The Keeling Curve of UCSanDiego. https://bluemoon.ucsd.edu/co2_400/mlo_full_record.pdf. Retrieved October 19, 2024.
7. Intergovernmental Panel on Climate Change. 2021. *Climate Change 2021: The Physical Science Basis*. https://www.ipcc.ch/report/ar6/wg1/. Retrieved October 19, 2024.
8. NASA. 2020. *NASA Earth Science: Climate Observations*. https://earthdata.nasa.gov/. Retrieved October 19, 2024.
9. United Nations Framework Convention on Climate Change. 2022. *Climate Action and the 2030 Agenda for Sustainable Development*. https://unfccc.int/. Retrieved October 19, 2024.
10. Pirani A, Matthews R and Chen L (eds). Intergovernmental Panel on Climate Change. 2023. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. IPCC, Geneva, Switzerland.
11. NOAA's National Centers for Environmental Information. 2024. Climate.gov. https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature. Retrieved October 19, 2024.
12. El-Montasser G and Salha OB. 2019. A new methodology for assessing the energy use-environmental degradation nexus. *Environmental Monitoring and Assessment* 191 (9): 587.
13. Hawkins E. 2021. The role of artificial intelligence in climate science. *Nature Climate Change*, 11 (5): 356-362.
14. World Meteorological Organization. 2023. *State of the Global Climate 2023*. https://library.wmo.int/viewer/68835/?offset=#page=1&viewer=picture&o=bookmark&n=0&q=. Retrieved October 19, 2024.

15. Pachauri RK. 2014. *Climate Change 2014: Synthesis Report*. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar5/syr/. Retrieved October 19, 2024.
16. Moser SC and Dilling L. 2004. Making climate hot: communicating climate change in the public sphere. *Environment*, 46 (10): 32-46.

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.

Original Article

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

JZ Yin[1,2,3] Ⓛ, Alice Shi[1], Haoyu Yin[4], Kuinuan Li[5] and Yuhong Chao[6]

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

---

Affiliation Info: [1] Orient Resources Ltd., Canada; [2] Wuhan Institute of Technology, Wuhan 430205, China; [3] College of Earth Sciences, Jilin University, Changchun 130061, China; [4] Guinea Westfield Mining Company, Plaza Diamant, kipe, Commune de Ratoma, Conakry-Guinee; [5] Henan Fanende Mining Co., Ltd., Luoning County, Luoyang City, 471700, China; [6] Engineering Geology Brigade, Jiangxi Bureau of Geology, Nanchang 330002, China

Article Info: Received: 21 September 2024 / Revised: 28 September 2024 / Accepted: 30 September 2024 / Published Online: 18 November 2024. www.naturalisscientias.com

Authors' Contact Info: Yin, JZ: jimyin7@yahoo.ca

Citation: JZ Yin, Alice Shi, Haoyu Yin, Kuinuan Li and Yuhong Chao. 2024. Types, genesis, characteristics and related topics of lithium ore deposits around the world. *Naturalis Scientias*, 1 (3): 228-253. DOI: https://doi.org/10.62252/NSS.2024.1017.

Corresponding AurhorⓁ: Yin, JZ, PhD, PGeo, Professor; Email: jimyin7@yahoo.ca

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).

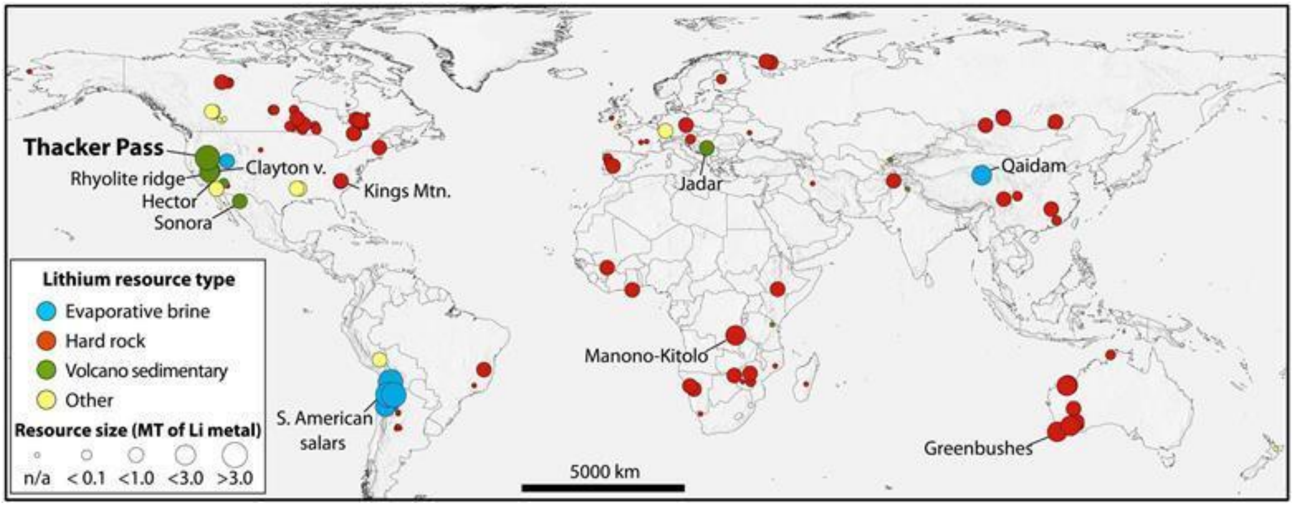


Figure 1. Map showing type and relative size of global lithium resources[1]

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

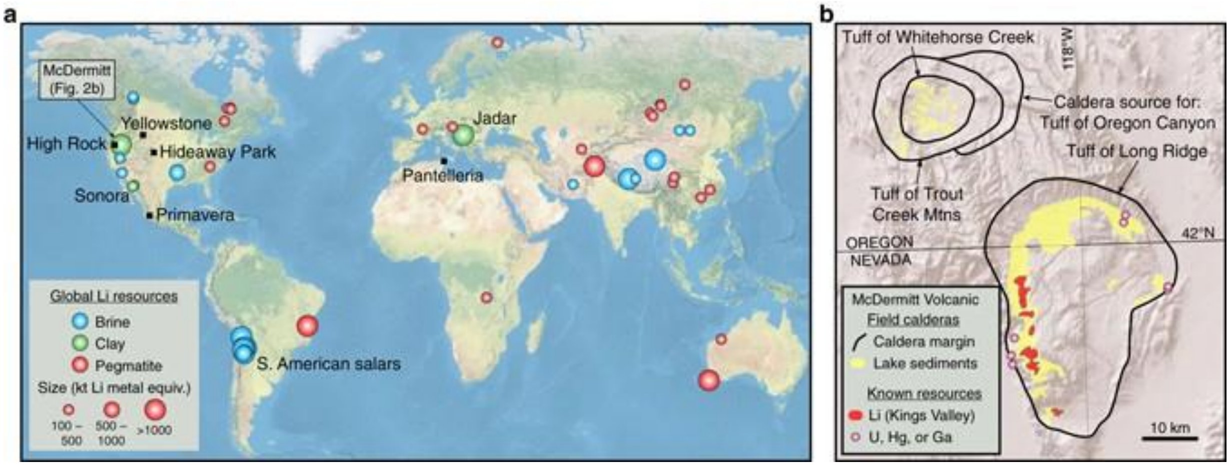


Figure 2. Location maps of global lithium resources and McDermitt volcanic field

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[2]

Regarding the classification of global lithium deposit types, geologists in many countries have made various attempts based on their own practices and understandings[3-14]. 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.

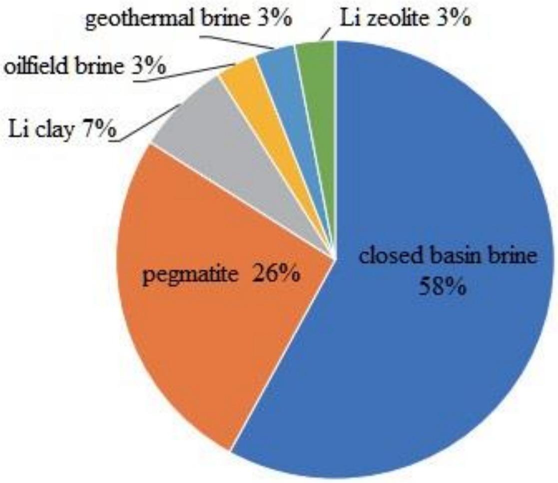


Figure 3. Global lithium deposit types and their proportions in 2020[15]

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	Endogenetic	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
		Pneumatolytic	Cryptoexplosive breccia	China, USA
		hydrothermal	Veinlet-dissemination	Note: Predicted new types to be discovered
			Skarn	
			K/Na-feldspar±fluorite± quartz vein	
		Metamorphic	Metamorphic	
	Exogenous	Sedimentary	Carbonate-clay-Li-Ga-REE	Carboniferous-Permian in Yunnan and Guizhou, China
			Claystone & clay	Yichang, China; Kings Valley, USA; Jadar, Serbia
			Paleosalt rock	China, USA
			Coal associated	China
Liquid		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[3-4, 8-11 & 16-23].

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[23].

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[22].

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[8-11 & 16-23].

Typical salt lake lithium deposits include Uyuni Salt Lake in Bolivia, Salarde 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[3-4, 8-11 & 16-23]:

- Uyuni Salt Lake lithium deposit in Potosi Province, Bolivia: The salt lake brine area is 10,582 km^2, the average depth of the salt layer is 121 m, the proven lithium reserves are 5.5 million tons, the Li_2O resources are about 18 million tons, and the lithium concentration of the brine is (80-1,150) × 10^{-6}.

- Atacama Salt Lake lithium deposit in Antofagasta Province, Chile: The salt lake brine area is 2,229 km^2, the salt layer depth is 360-400 m, the Li_2O resource is approximately 5.3 million tons, and the brine lithium concentration is (1,000-4,000) × 10^{-6}.

- Litio Salt Lake lithium deposit in Antofagasta Province, Chile: The salt lake resources are 3.2 billion m^3, 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^2, with an estimated lithium brine content of 800 billion tons, Li_2O resources of approximately 850,000 tons, and brine lithium concentration of (220-1,000) × 10^{-6}.

- Cauchari-Olaroz Salt Lake lithium deposit in Jujuy Province, Argentina: The total resources of the salt lake are 4.575 billion m^3, containing 2.7402 million tons of lithium and a lithium grade of 0.06%. The reserves are 7.710 billion m^3, 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_2O resources 1.573 million tons, Li_2O 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_2CO_3 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 24×10^{-6} - 110×10^{-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[3-4 & 7-15].

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.

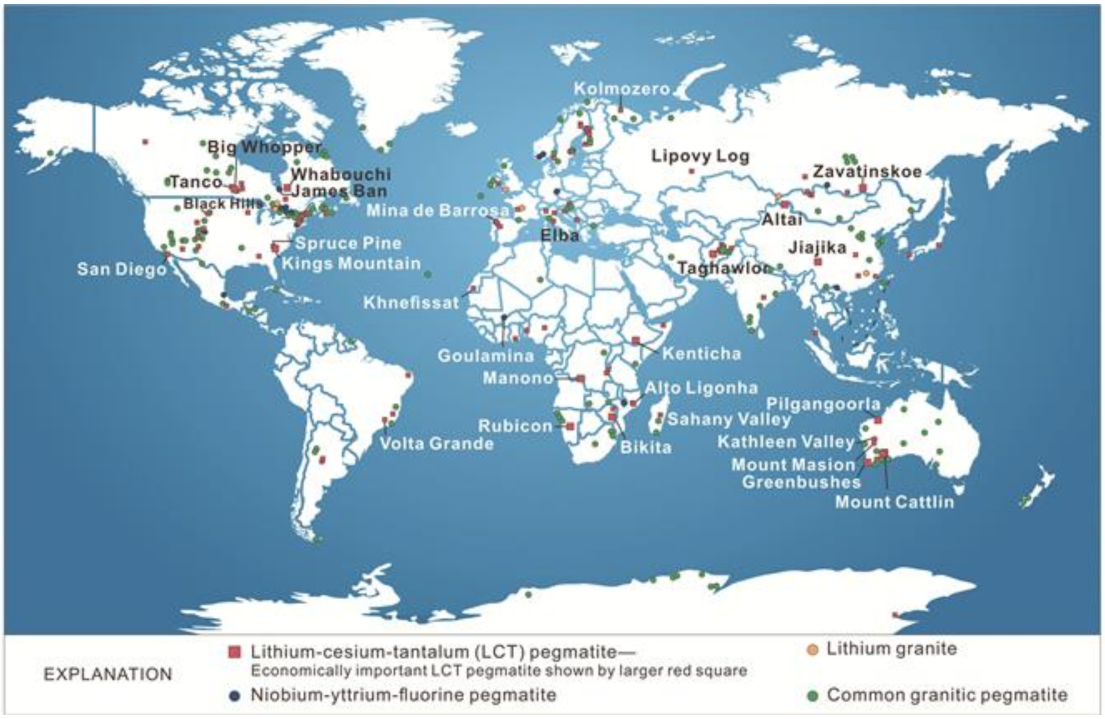


Figure 4. Distribution map of the world's major LCT pegmatite lithium deposits[5]

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)[4, 7, 10-13, 15 & 24-33]. 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[25]. 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[10-13].

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[15 & 24-33].

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[8-14, 16, 18 & 25].

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 Li_2O grade of 1.22%[28].

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 Li_2O grade of 0.43%, that is, the Li_2O 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 Li_2O grade of 0.43% and a tin grade of 0.04%.

The Taghawlor pegmatite lithium deposit in Uruzgan Province, Afghanistan, has a Li_2O resource of 1.46 million tons and a lithium grade of 0.08%-2.80%[35].

The pegmatite lithium deposit in Yichun, Jiangxi, China, has a total ore of 150 million tons and a Li_2O resource of 510,400 tons[36].

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[4, 7, 10-13, 15 & 24-36].

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-cesium, etc. The lithium minerals are mainly spodumene, and there are also lithium mica and iron lithium mica. The Li_2O 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[8-14, 16, 18 & 25].

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 (H_2O, 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[4, 7, 10-13, 15 & 24-36]. 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[13]. 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[32-33].

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[37]. 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[35].

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[38].

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_2O grade is between 0.8% and 3.6%, with an average grade of 1.25%. The Rb_2O 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_2O is 357,000 tons, and the grade is 1.28%. Rb_2O 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[38].

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[2].

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[4, 10-11, 15, 24 & 39-42].

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[4]. 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 Li_2O 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 Li_2O is as high as 7.3%. The current estimated Jadar lithium ore is 114.6 million tons, with a Li_2O grade of 1.8%, that is, the Li_2O resource can reach 2.06 million tons[41]. 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 Li_2O 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 Li_2O 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 sedimentray 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[43-44]. 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[2 & 22]. 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)[22]. Later hydrothermal/brine alteration is also one of the key factors in the formation of these lithium deposits.

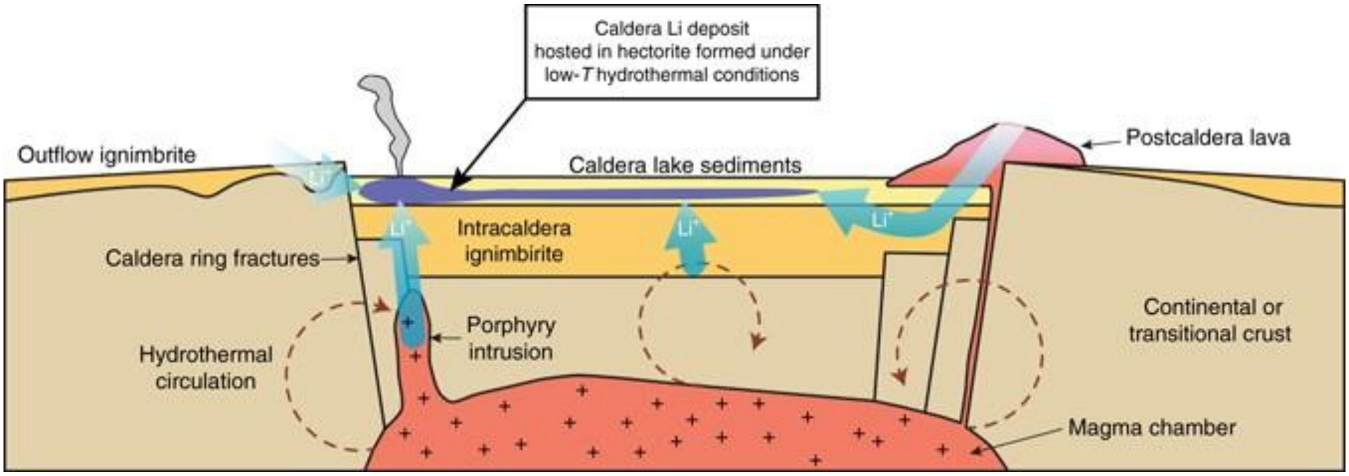


Figure 5. Schematic model for the formation of caldera-hosted Li clay deposits

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[2]

3.2 Enrichment mechanism

The unique adsorption effect of carbon and some clay minerals[45] 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[43-44].

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[43-44].

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.

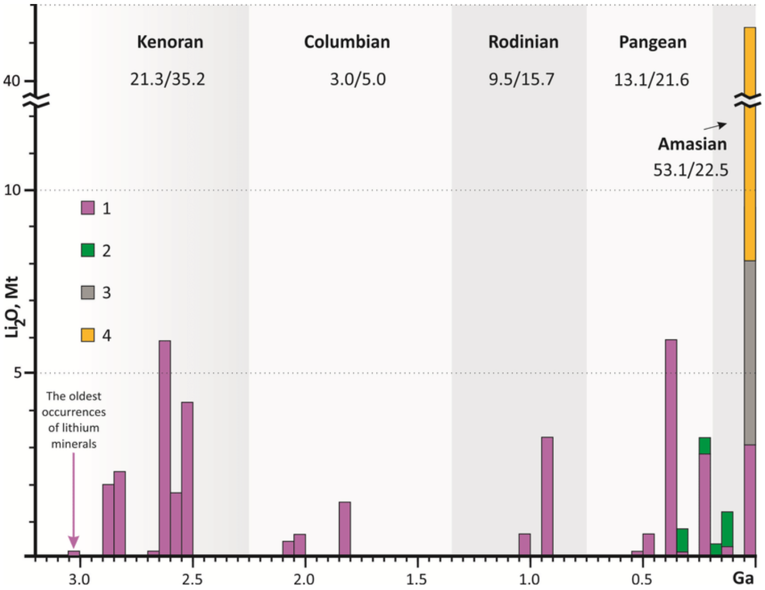


Figure 6. Distribution of lithium resources accumulated in LSLDs through geological time

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[24].

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[2 & 22].

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_2O, 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[46].

Li et al. divided the country into 12 lithium mineralization belts based on the distribution pattern of lithium deposits in China[13]：

- **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 Jianghan Basin mineralization belts.

According to Gruber and Medina of the University of Michigan6, 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.

9 References

1. Benson TR, Matthew AC & Dilless JH. 2023. Hydrothermal enrichment of lithium in intracaldera illite-bearing claystones. *Science Advances*, 9 (35). DOI: 10.1126/sciadv.adh8183.

2. Benson TR, Coble MA, Rytuba JJ & Mahood, GA. 2017. Lithium enrichment in intracontinental rhyolite magmas leads to Li deposits in Caldera basins. *Nat Commun*, 8, 270.DOI: https://doi.org/10.1038/s41467-017-00234-y.

3. Garrett D. 2004. *Handbook of lithium and natural calcium chloride: Their deposits, processing, uses and properties*. Elsevier Academic Press: 651.

4. Kesler SE, Gruber PW & Medina PA. 2012. Global lithium resources: Relative importance of pegmatite, brine and other deposits. *Ore Geology Review*, 48: 55-69. DOI: 10.1016/j.oregeorev.2012.05.006.

5. Groves DI, Zhang L, Groves IM and Sener AK. 2022. Spodumene: The key lithium mineral in giant lithium-cesium-tantalum pegmatites. *Acta Petrologica Sinica*, 38 (1): 1-8 (in Chinese with English abstract). DOI: 10.18654/1000-0569/2022.01.01.

6. Gruber PW, Medina PA, Keoleian GA, Kesler SE, Everson MP & Wallington TJ. 2011. Global lithium availability：A constraint for electric vehicles? *Journal of Industraial Ecology*. https://doi.org/10.1111/j.1530-9290.2011.00359.x.

7. Tkachev AV. 2011. Evolution of metallogeny of granitic pegmatites associated with orogens throughout geological time, Granite-Related Ore Systems. *Geological Society, London, Special Publications*, 350: 7-23. DOI: 10.1144/SP350.2.

8. Liu LJ, Wang DH & Liu XF. 2017. Main types, distribution characteristics and exploration and development status of lithium mines at home and abroad. *China Geology*, 44 (2): 263-278. https://www.cnki.com.cn/Article/CJFDTOTAL-DIZI201702005.htm.

9. Wang DH, Dai HZ & Liu SB. Research and exploration progress on lithium deposits in China. China Geology, 2020, 3 (1): 137-152. DOI: 10.31035/cg2020018.

10. Zhang B, Qi FY & Gao XZ. The geological characteristics, metallogenic regularity, and research progress of lithium deposits in China. *China Geology*, 2022, 5 (1): 1-34. DOI: 10.31035/cg2022001.

11. Xi WW, Zhao YH & Ni P. 2023. Analysis of main types, characteristics, spatial and temporal distribution and prospecting potential of lithium deposits. *Sedimentary and Tethyan Geology*, 1: 21-37. https://www.cnki.com.cn/Article/CJFDTOTAL-TTSD202301002.htm.

12. Lou DB, Wang DH, Li WY, Fan YL, Liu H & Du XH. 2022. Research progress on prospecting and prediction of granite pegmatite-type lithium deposits at home and abroad. *Mineral Deposit Geology*, 41 (5): 975-988. DOI:10.16111/j.0258-7106.2022.05.006.

13. Li Jk, Liu XF & Wang DH. 2014. Summary of lithium mineralization law in China. *Acta Geologica Sinica*, 88 (12): 2269-2283.

14. Chen XK & Zhou ZH. 2023. Deposit types, metallogenesis and resource prospect of Li-Be-Nb-Ta deposits in the Great Xing'an Range. *Acta Petrologica Sinica*, 39 (7): 1973-1991. DOI: 10.18654/1000-0569/2023.07.06.

15. USGS. Mineral Commodity Summaries (2011-2022). 2022. http://minerals.usgs.gov/minerals/pubs/mcs/2011-2022.pdf.

16. Zhai MG, Wu FY, Hu RZ, Jiang SY, Li WC, Wang RC, Wang DH, Qi T, Qin KZ & Wen HJ. 2019. Strategic critical metal mineral resources: current status and problems. *Chinese Science Foundation*, 33 (2): 106-111.

17. Moores S. 2007. Between a rock and a salt lake. *Industrial Minerals*, 477: 58.

18. Chen YM & Deng XL. 2013. Potential and development of lithium resources in Argentina. *Salt Lake Research*, 4: 67-72. https://www.cnki.com.cn/Article/CJFDTOTAL-YHYJ201304015.htm.

19. Lowenstein T & Risacher F. 2009. Closed basin brine evolution and the influence of Ca-Cl inflow waters. Death Valley and Bristol Dry Lake, California, Qaidam Basin, China, and Salar de Atacama, Chile. *Aquatic Geochemistry*, 15 (1/2): 71-94.

20. Song PS & Xiang RJ. 2014. Development and utilization of salt lake lithium resources and suggestions for the development of China's lithium industry. *Mineral Deposit Geology*, 33 (5): 977-992. https://www.cnki.com.cn/Article/CJFDTOTAL-KCDZ201405007.htm.

21. Risacher F & Fritz B. 1991. Quaternary geochemical evolution of the salars of Uyuni and Coipasa. central Altiplano, Bolivia. *Chemical Geology*, 90: 211-231. DOI: 10.1016/0009-2541(91)90101-V.

22. Ericksen GE & Salas R. 1987. Geology and resources of Salars in the central Andes. *United States Geological Survey, open-file report*, 1987: 88-210, 51.

23. Collins A. 1976. Lithium abundances in oilfield waters. *USGS Professional Peper Report*: p 1005, pp 116-123.

24. Tkachev AV, Rundqvist DV & Vishnevskaya NA. 2018. Metallogeny of lithium through geological time. *Russian Journal of Earth Sciences*, 18 (6): 1-13. DOI: 10.2205/2018ES000635

25. Chen YJ, Xue LZ, Wang XL, Zhao ZB, Han JS & Zhou KF. 2021. Progress in geological study of pegmatite ・ type lithium deposits in the world. *Acta Geologica Sinica*, 95 (10): 2971-2995.

26. Dewaele S, Hulsbosch N & Cryns Y. 2016. Geological setting and timing of the world-class Sn, Nb-Ta and Li mineralization of Manono-Kitotolo (Katanga, Democratic Republic of Congo). *Ore Geology Reviews*, 72: 373-390. DOI: 10.1016/j.oregeorev.2015.07.004.

27. Harris PD, Robb LJ & Tomkinson MJ. 1995. The nature and structural setting of rare-element pegmatites along the nothern flank of the Barberton greenstone belt, South Africa. *South African Journal of Geology*, 98 (1): 82-94.

28. Partington GA, McNaughton NJ & Williams IS. 1995. A review of the geology, mineralization and geochronology of the Green bushes pegmatite, WesternAustralia. *Economic Geology*, 90: 616-635. DOI: 10.2113/gsecongeo.90.3.616.

29. Xu ZQ, Wang RC & Zhao ZB. 2018. On the tectonic setting of the "hard rock type" large lithium mineralization belt in mainland China. *Acta Geologica Sinica*, 92 (6): 1091-1106. https://www.cnki.com.cn/Article/CJFDTOTAL-DZXE201806001.htm.

30. Xu ZQ, Fu XF, Zhao ZB, Li GW, Zheng YL & Ma ZL. 2019. Discussion on the mineralization law of gneiss dome and pegmatite type lithium deposits. *Earth Science*, 44 (5): 1452-1463．

31. Grew E S, Bosi F & Gunter ME. 2018. Fluor-elbaite, lepidolite and Ta-Nb oxides from a pegmatite of the 3000 Ma Sinceni pluton, Swaziland: Evidence for lithium-cesium-tantalum (LCT) pegmatites in the Mesoarchean. *European Journal of Mineralogy*, 30 (2): 25-39.

32. Zhang H, Lü ZH & Tang Y. 2019. Mineralization regularity, prospecting model and prospecting direction of pegmatite-type rare metal deposits in the Altai orogenic belt of Xinjiang. *Mineral Deposit Geology*，38 (4): 792-814.

33. Zhang H, Lü ZH & Tang Y. 2021. Overview of the genesis of LCT-type pegmatites and their lithium deposits. *Acta Geologica Sinica*, 95 (10): 2955-2970. DOI:10.3969/j.issn.0001-5717.2021.10.003.

34. Wikipedia. 2023. Lithium. Available from: https://en.wikipedia.org/wiki/Lithium.

35. Risen J. U.S. Identifies Vast Riches of Minerals in Afghanistan. *The New York Times*. 13 June 2010.

36. Wan TA, Chen TC, Chen JJ, Ling MX, Cai F & Xu DR. 2022. Study on the element enrichment mechanism of the Yichun 414 tantalum-niobium deposit. *Journal of East China University of Technology (Natural Science Edition)*, 45 (6): 514-537. DOI:10.3969/j.issn.1674-3504.2022.06.002.

37. Fu XF, Liang B, Zou FG, Hao XF & Hou LW. 2021. Analysis on the geological characteristics and genesis of the Jiajika lithium polymetallic ore field in western Sichuan, China. *Acta Geologica Sinica*, 95 (10): 3054-3068. DOI:10.3969/j.issn.0001-5717.2021.10.008.

38. Li BY, Jiang DW, Fu X, Wang L, Gao SQ, Fan ZY, Wang KX & HuGejiletu. 2018. Geological characteristics and prospecting significance of lithium polymetallic deposits in Weilastuo mining area, Inner Mongolia. *Mineral Exploration*, 9 (6): 1185-1191. DOI:10.3969/j.issn.1674-7801.2018.06.021.

39. Gong Y, Zheng F, Zhou Z, Lei L, Zou X, Xiang M, Qiu F, Yang P, Zhang Y, Lu JX, Chen BH & Yan L. 2023. Characteristics and comparative study of lithium-rich claystones in the Liangshan and Longtan formations of the Permian in Yichang area. *Resources Environment and Engineering*, (5): 521-529 .

40. Yu F, Wang DH & Yu Y. 2019. Distribution, exploration and development status of major sedimentary lithium deposits at home and abroad. *Rock and Mineral Testing*, 38 (3): 354-364. https://www.cnki.com.cn/Article/CJFDTOTAL-YKCS201903013.htm.

41. Zhao YY, Fu JJ & Li Yun. 2015. Super-large lithium-boron deposit in the Jadar Basin, Serbia. *Geological Review*, 1: 34-44. https://www.cnki.com.cn/Article/CJFDTOTAL-DZLP201501003.htm.

42. Stanley C et al. 2007. Jadarite, LiNaSiB3O7(OH), a new mineral species form the Jadar Basubm, Serbia. *Eur. J. Mineral*, 9: 575-580.

43. Yin JZ. 1994m. Nano-mineral deposit. *Earth Science Frontiers*, 1 (4): 8 (in Chinese).

44. Yin JZ & Shi HY. 2019b. Nano effect mineralization of rare elements-taking the Dashuigou tellurium deposit, Tibet. *Academia Journal of Scientific Research*, 7 (11): 635-642. DOI: 10.15413/ajsr.2019.0902.

45. Ren HM & Yin JZ. 1989. Function of carbon on the forming of gold deposits. In: Committee of Mineral Deposits of China Society of Geology (ed.). *Collection of abstracts of the 4th China National Congress of Mineral Deposits Volume 1*: 257-258 (in Chinese).

46. Wang XQ, Liu HL, Wang W, Zhou J, Zhang BM & Xu SF. 2020. Geochemical background and spatial distribution of lithium deposits in China: prediction of prospective areas. *Acta Geoscientia Sinica*, 41 (6): 797-806.

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.

Brief Report

Brief discussion on tectonic uplift of the Yandang Mountain, Zhejiang Province, China

Jijun Zhang[1] ©

Yandang (also known as Yandangshan) Mountain in Yueqing City, Zhejiang Province, at 27°50′～28°30′ N and 120°27′～120°41′ E, with a total area of 450 square kilometers, is tectonically located in the eastern Cathaysia Block. It is famous for its grotesque topography and beautiful scenery. It is not only historically known as the "No. 1 Mountain in Southeast China", but also called the "Natural Museum" by Chinese and foreign geologists. In 2005, UNESCO Global Geoparks Council announced in Paris that Yandang Mountain was selected as a Global Geopark.

Before the 1980s, Yandang Mountain did not receive much attention from geologists. It was not until the 1990s that Yandang Mountain indeed came into the eyes of science, and in-depth research was conducted extensively. However, most of the studies at that time focused on the higher altitude areas of Yandang Mountain, namely, on the volcanic rock areas, while insufficient studies were done on the basal area of the mountain. The reason for this may be that the surface of basal mountain rocks is usually covered with a layer of black oxide, fluvial and alluvial materials, without distinct outcrops. Therefore, they are often overlooked and mistaken for volcanic rocks. With the in-depth development and road reshaping of this world geopark, more and more roadcut rocks are beginning to be exposed in front of our eyes.

Previous studies show that Yandang Mountain is a typical caldera erupted from late Mesozoic rhyolitic magma on the southeastern coast of China. Volcanic eruption was initiated in the Hauterivian Stage of the Cretaceous about 130 million years ago, which developed an amazing variety of the Cretaceous rhyolite landforms[1].

Key words: Yandang Mt.; rhyolite; pyroclastic flow; uplift; diorite porphyrite; syenite; Plinian eruption

---

Affiliation Info: [1] 28 Ann Louise Crescent, Markham, ON L3S 0A8, Canada

Article Info: Received: 16 November 2024 / Revised: 18 November 2024 / Accepted: 18 November 2024 / Published Online: 18 November 2024. www.naturalisscientias.com

Authors' Contact Info: Zhang, J: jijun_z@yahoo.ca

Citation: Zhang, J. 2024. Brief discussion on tectonic uplift of the Yandang Mountain, Zhejiang Province, China. *Naturalis Scientias*, 1 (3): 254-259. DOI: https://doi.org/10.62252/NSS.2024.1018.

Corresponding Aurhor ©: Zhang, J, PhD in marine geology, micropaleontology and paleoceanography, professor, petroleum geologist and editor; Email: jijun_z@yahoo.ca

Because of the westward subduction of the Paleo-Pacific Plate (or called the Izanagi Plate), Yandang Mountain, as an important part of the Pacific Rim tectonic system, developed a series of large-scale volcanic activities during the Late Mesozoic (Cretaceous). As a result, 4 phases of volcanic eruptions (KY1-KY4), and a final phase of central subvolcanic intrusion (hypabyssal intrusion) in calderas took place as follows：

- Phase I, known as Plinian eruption occurred 128 million years ago (Hauterivian Stage). It is characterized by pyroclastic flow facies, predominated by rhyolitic welded crystal-lapilli tuffs and low silicon rhyolitic ignimbrites identified as Formation KY1.
- Phase II Eruption took place about 121 million years ago. The lithofacies are mostly ignimbrites, pyroclastic flow deposits, and massive or flow-banded rhyolite with enriched spherulites and occasional lithophysae (Formation KY2).
- Phase III Eruption occurred about 104 million years ago. It is characterized by pyroclastic flow and effusive facies, which are predominated by rhyolitic lapilli tuffs and interlayered rhyolites (Formation KY3)[2,3].
- Phase IV Eruption was the last violent Plinian eruption estimated about 99 million years ago. This phase is dominated by rhyolitic welded crystal-vitric ignimbrites of pyroclastic flow facies with well-developed columnar joints and eutaxitic texture, and local effusive tuff lava (Formation KY4).
- Phase V is a central subvolcanic intrusion in Caldera occurred about 98 million years ago (Turonian Stage) as estimated[4]. The lithofacies are predominated by the intermediate grained quartz syenites (Formation KY), which marked the end of the volcanic activities in Yandang Mountain[3].

This fall, I had the privilege of revisiting Yandang Mountain and consciously browsed its geology and rocks. On several roadcuts, I found rocks that were different from those I had seen before (Figure 1), and have never been reported, which encouraged me to write this short article.

Figure 1. Location map of study area. Base map is from Google Map

As shown in Figure 2, multitudinous hydrothermal quartz veins intruded vertically into the fractured parent rock known as diorite-porphyrite proposed by Prof. Duan (Zheng Duan, personal communication, Nov. 2024). The vertical veins are approximately a few centimeters to about 20 centimeters in width.

Figure 2. Showing diorite-porphyrite and hydrothermal quartz veins at Site A

Hydrothermal quartz veins are formed by hydrothermal fluids under high temperature and pressure. Hydrothermal fluids are high-temperature, high-pressure fluids rich in water, which are common in underground rocks. When hydrothermal fluids flow into rock cracks or faults, and meet certain temperature and pressure conditions, veins containing quartz will precipitate, forming hydrothermal quartz veins.

Diorite-porphyrites are also discovered at sites B and C, only about 1 km away to the west from Site A (Figures 3 and 4a).

Figure 3. Showing diorite-porphyrite and joints at Site B

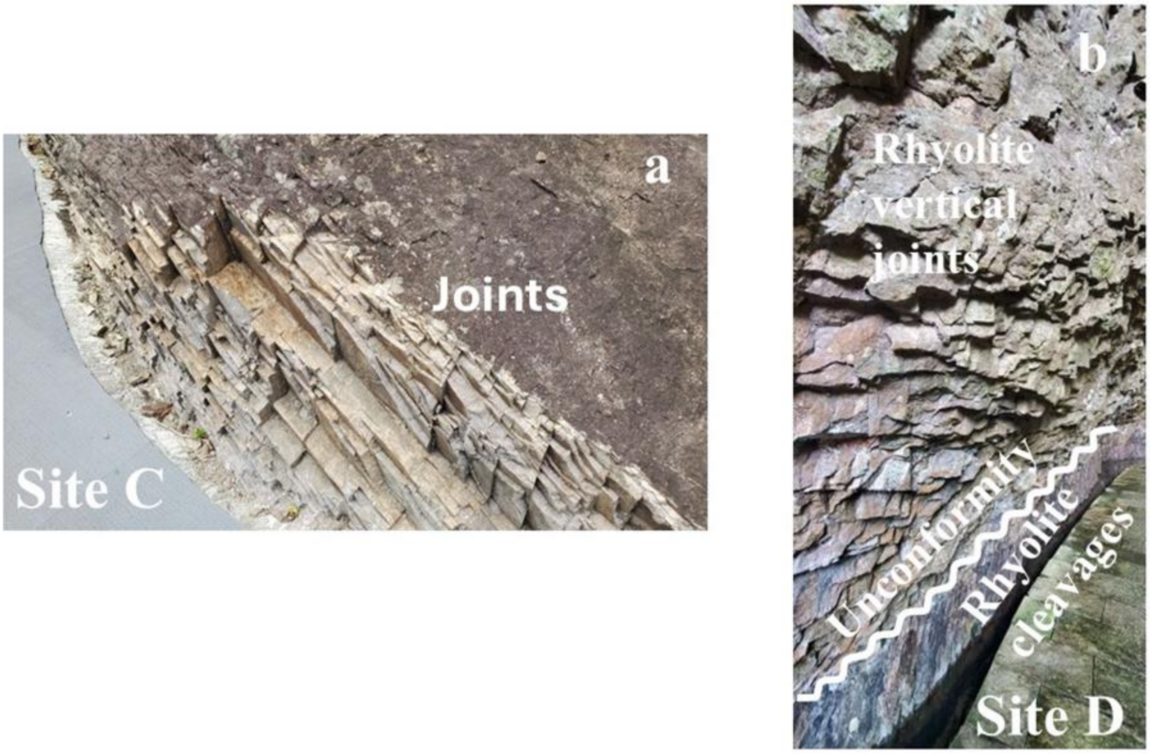


Figure 4. **a**: Showing diorite-porphyrite and joints at Site C; **b**: Showing rhyolite with dense vertical joints, cleavages and an unconformity from the Middle Tier Falls, Yandang Mt., Site D

At the Middle Tier Falls (See Site D) at the scenic spot of Three Tier Falls, rigid rhyolite with dense vertical joints overlies the rhyolite with slightly tilted cleavages, separated by an unconformity. It may imply that 2 phases of volcanoes could exist here before, possibly the Phase I and Phase II volcanoes in Yandang Mt (Figure 4b). Figures 2-4 indicate that this area has experienced violent tectonic movement and uplifting.

Assuming that the diorite-porphyrite and hydrothermal quartz veins were formed two kilometers underground, then the total amplitude of tectonic uplift in the Yandang Mt area could be at least 2,000 meters. This is consistent with Duan Zheng's study, who proposed that Yandang Mountain has been uplifted three times, with a total amplitude of approximately 1,400-1,750 meters (Duan)[5]. This magnitude is not surprising. Since the late Mesozoic, the world has experienced intense Yanshan orogeny and Himalayan orogeny, causing the Himalayan Mountains to rise about 10,000 meters from sea floor, the Alps to 4,800 meters, and the Andes to 6,960 meters. In addition, the Sirt Basin (Sahara Desert) in eastern Libya has subsided by an average of at least 5,000 meters[6].

In addition, based on the discovery of the pebble deposit near the top of Daping Mt , Ruili Town, Yueqing City (Figure 5), and other studies[5,7], it is postulated that the study area suffered strong vertical uplift during the middle Miocene (ca 12 million years ago). The current altitude of Daping Mt is estimated about 100 meters above the sea-level. Here, I assume that the uplift of the Daping Mountains mainly occurred in the last large-scale uplift of the Late Cenozoic Era (middle Miocene).

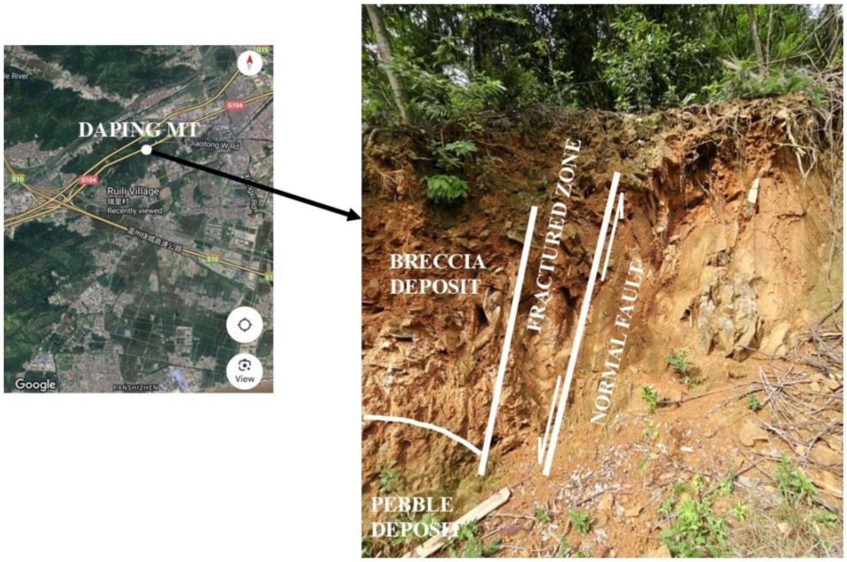


Figure 5. Pebble deposit at lower-left corner is overlain by breccia deposit near the top of the Daping Mt, Ruili Town, Yueqing City, Zhejiang Province, China

It is presumed that the uplift in the middle Miocene is related to the collision of the Australian Plate and the Philippine Sea Plate, causing the Philippine Sea Plate to drift northward. The uplift amplitude in this period may have exceeded 100 meters, while Prof. Duan proposed the uplift amplitude of 100-200 meters[7]. As the Philippine Sea Plate and the Paleo-Pacific Plate (Izanagi Plate) continued to subduct westward, the eastern continental margin of China, including Yandang Mountain, was violently compressed and uplifted[8]. The large-scale plate collision not only triggered the uplift of Yandang Mountain, but also triggered numerous shield volcanic eruptions on both sides of the Yangtze River. In the past 2 million years, as Taiwan Island separated from Luzon Island and drifted northwestward rapidly[9] (at a speed of 6-8 cm per year), China's eastern continental margin has been undergoing compression and uplift, and this uplift may still continue today.

Acknowledgements

The author gratefully thanks Prof. Zheng Duan at Nanjing Geological Center of China Geological Survey, Nanjing, Jiangsu Province for his valuable discussion on several important issues of the Yandang Mountain, and identification of diorite-porphyrite rock.

References

1. Institute of Geography and Environmental Sciences, Zhejiang Normal University, Jinhua, Zhejiang, 2018. Geomorphological characteristics and origin of volcanic rocks in the Yandang Mountain. *Institute of Geology and Geosciences, Chinese Academy of Sciences*. https://m.163.com/dy/article/DS7E5I840512TGD9.html.

2. Yan, LL; He ZY; Beier, C & Klemd R. 2018. Zircon trace element constrains on the link between volcanism and plutonism in SE China. *Lithos*, 320-321: 28–34. https://doi.org/10.1016/j.lithos.2018.08.040.

3. Yan, LL; He ZY; Jahn, BM & Zhao ZD. 2016. Formation of the Yandangshan volcanic–plutonic complex (SE China). *Lithos*, 266–267: 287–308. DOI: http://dx.doi.org/10.1016/j.lithos.2016.10.029.

4, Hu, X; Xu, H; Chen, M; Li, Y; Wang, D & Chen, M. 2008. Rhyolite landform characteristics and its law of formation and development in the Yandang Mountain. *Acta Geographica Sinica*, 63 (3): 270-279 (in Chinese with English Abstract).

5. Duan, Z; Zhang, X; Lu, Q; Chen, R; Yu, M; Hong, W & Chu, P. 2022. The origin of the Yandang Mountain landforms in Zhejiang in the late Mesozoic and its coordinated evolution with volcanic structures. *Acta Geologica Sinica*, 96 (6), 2021-2038 (in Chinese with English abstract).

6. Zhang, J. 2013. Silicified microfossils in the Nubian (Albian) Sandstone of Sirt Badin, Libya: A key to the basin history. *Micropaleontology*, 59 (1): 49-58. DOI: 10.47894/mpal.59.1.02.

7. Wang, X; Suo, Y; Li, S; Cao, X; Li, X; Zhou, J; Wang, P & Jin, C. 2020. Cenozoic uplift history and its dynamic mechanism along the eastern continental margin of South China. *Acta Petrologica Sinica*, 36 (6): 1803-1820 (in Chinese with English abstract).

8. Zheng, Q; Zhou, Z; Cai, L; Lu, Y & Cao, Q. 2005. Meso-Cenozoic tectonic setting and evolution of the East China Sea shelf basin. *Oil & Gas Geology*, 26 (2): 197-201 (in Chinese with English abstract).

9. Liang, G. 2013. Research on the origin of the Taiwan Island and Huangyan Island. *Geographical Science Research*, 2 (2): 44-56. DOI: http://dx.doi.org/10.12677/GSER.2013.22006.

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.

Book Review

A complete chronicle of Chia Yung Hsieh (C. Y. Hsieh) and his life and works

JZ Yin[1,2,3] Ⓛ

Abstract

In the process of pioneering and developing China's geological career, Mr. Hsieh created numerous firsts in Chinese geological sciences. Some of them were even the first in the world. Hsieh has been a unique all-round geologist in the Chinese geological community. His research fields include general geology, regional geology, stratigraphy, structural geology, geotectonics, mineralogy, petrology, paleontology, meteorite science, hydrogeology and engineering geology, seismology, lithofacies and paleogeography, physiography and geomorphology, pedology, coal petrology, coal geology, petroleum geology, mineralogy, mineral deposits, economic geology, core drilling, geophysics, geochemistry, prospecting and exploration geology, and geological technology management, etc. Hsieh has conducted in-depth research or application in all the above disciplines and has achieved remarkable and great achievements. In many aspects, he has occupied a pioneering position in China geological community. He is a well-deserved pioneer and founder of modern Chinese earth sciences. In terms of geological education in China, Hsieh's students are spread across different regions of China. In 1913, Hsieh entered the Institute of Geology， Ministry of Industry and Commerce, to study geology. Hsieh was recommended to study in the Department of Geology at Stanford University in 1917. In 1919, he transferred to the Department of Geology at the University of Wisconsin and received a Master of Science degree in 1920. All of these are documented in detail in the book titled *A Complete Chronicle of C. Y. Hsieh*, which was completed by researcher Lisheng Zhang after eight years of hard work and countless efforts. The book consists of two volumes, large 16 mo format, with rich illustrations and text, totaling 1,203 pages and 1,444,000 Chinese characters. The book was published by the Shanghai Jiao Tong University Press in December 2022.

Key words: Chia Yung Hsieh (C. Y. Hsieh); a complete chronicle; a pioneering geologist in China; a unique all-round geologist; suicide

---

Affiliation Info: [1] College of Earth Sciences, Jilin University, Changchun 130061, China; [2] Wuhan Institute of Technology, Wuhan 430205, China; [3] Orient Resources Ltd., Canada

Article Info: Received: 15 August 2024 / Revised: 21 August 2024 / Accepted: 18 September 2024 / Published Online: 18 November 2024. www.naturalisscientias.com

Authors' Contact Info: Yin, JZ: jzyin7@jlu.edu.cn

Citation: Yin, JZ. 2024. A complete chronicle of Chia Yung Hsieh（C. Y. Hsieh） and his life and works. *Naturalis Scientias*, 1 (3): 260-285. DOI: https://doi.org/10.62252/NSS.2024.1019.

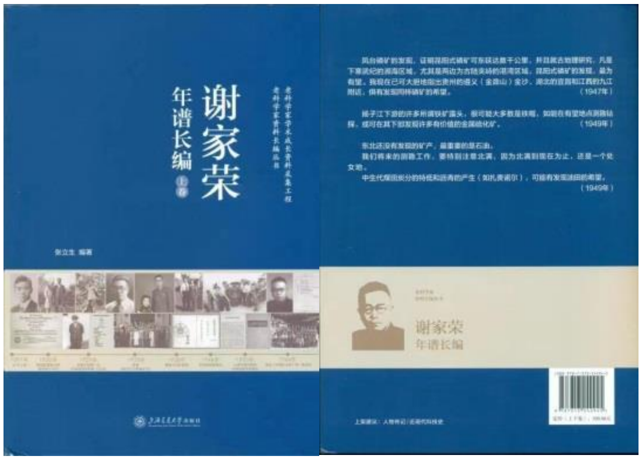
Corresponding AurhorⓁ: Yin, JZ, PhD, PGeo, Professor; Email: jzyin7@jlu.edu.cn

1 Introduction

In the early days of modern sciences in China, especially geological sciences, Mr. Chia Yung Hsieh (C. Y. Hsieh) was an extraordinary figure that could not be ignored, even though his life ended in an incredible tragedy. It is said to be a tragedy because the mental and physical suffering he suffered in his later years and the abnormal way his brilliant life ended were seriously disproportionate to his great contributions to China's geological sciences and mineral development, and even completely put the cart before the horse. I am not saying this without basis. Just look at his unparalleled and great contributions to the establishment and development of China's geological sciences and related disciplines, various geological explorations, mining developments and economic development, and then compare it with his untimely death, and you will understand the sadness and even tragedy of it.

In the process of pioneering and developing China's geological career, Mr. Hsieh created numerous firsts in Chinese geological sciences. Some of them were even the first in the world. However, due to the completely unreasonable extreme political environment at that time, that is, the extreme left social atmosphere of politics in command and politics first, even a great scientist like Mr. Hsieh, who made unprecedented and great contributions to modern Chinese science and technology and was known as a versatile geologist, was banished to the cold palace for a long time after 1950, and finally committed suicide after being criticized and humiliated. What's more, his great oil prospecting achievements during his lifetime were plundered by the political celebrities and his former colleagues at that time, and so on. All of these are documented in detail in the book A Complete Chronicle of C. Y. Hsieh, which was completed by researcher Lisheng Zhang after eight years of hard work and countless efforts. In a sense, rather than saying that this book is a chronology of Mr. Hsieh, it is better to say that it is a detailed reflection and empirical evidence of modern Chinese geological career and social conditions.

The book consists of two volumes, large 16mo format, with rich illustrations and text, totaling 1,203 pages and 1,444,000 Chinese characters. The book was published by Shanghai Jiao Tong University Press in December 2022 (Figure 1, hereafter referred to as the Chronicle).



老科学家学术成长资料采集工程
老科学家资料长编丛书

谢家荣
年谱长编
下卷

张立生 编著

Figure 1. The book *Complete Chronicle of Chia Yung Hsieh*

2 Created many firsts in China's geological science community

According to the meticulous research of *the Chronicle*, Mr. Hsieh created at least the following firsts in Chinese earth sciences during his geological career before he was forced to commit suicide, and made tremendous contributions to the establishment and development of the country's geological sciences and the exploration and development of various mineral resources:

- Hsieh was one of the first 28 Chinese geologists ever trained by the Chinese people. He graduated from the Institute of Geology, China's first real scientific institution, in 1916 (Figure 2).

Figure 2. A group photo of some students from the Institute of Geology in 1915
(Hsieh is the second from the right.)

- Hsieh was the first graduate of the Chinese Institute of Geology to be sent abroad to study, and in 1917 he went to Stanford University in the United States for further studies (Figure 3).

Figure 3. Photo taken in California, USA in December 1918 when Hsieh was studying at Stanford University

- Hsieh was one of the first few Chinese geologists to conduct field research on the Haiyuan earthquake in northwest China from April 15 to August 15, 1921 (Figure 4).

Figure 4. Mr. Wen-hao Wong (W. H. Wong) (left) and C. Y. Hsieh (right) during the investigation of the Gansu super-earthquake in 1921

(Photo taken at Sunjiagou, Hsisiang rural community, Jingning County, Gansu Province)

- Shortly thereafter, Hsieh wrote China's first earthquake geological survey report; namely, Report on the Gansu Earthquake in December 1920.
- From August 16 to November 21 of the same year, Hsieh conducted geological and petroleum geological surveys in Gansu. This was the first petroleum geological survey conducted by Chinese geologists in China. As a result, Hsieh became China's earliest petroleum geological science investigator.

- In the winter of the same year, Hsieh and his colleague Professor P. L. Yuan first proposed the establishment of the Geological Society of China to facilitate academic exchanges and exchange of geological journals with overseas geological societies.
- In May 1922, Hsieh compiled China's first petroleum geological survey report; namely, the Gansu Yumen Petroleum Report, which was published in the 54th issue of *Industrial Magazine* published in Hunan, China.
- Hsieh completed the first monograph on coal geology in China, namely *The Coal*, which was published by Shanghai Commercial Press in January 1923. It was the tenth volume of the encyclopedia series that year.
- Hsieh pioneered the scientific research of meteorites in China. On June 15, 1923, at the Sixth Plenary Session of the Geological Society of China, he read the paper On the composition and structure of the first specimen of meteoric stone received by the Geological Survey of China, which was published in the eighth issue of the eighth volume of *Science* in August of the same year. In January 1924, Hsieh further published A Brief Introduction to Meteorites in the first issue of the ninth volume of *Science*.
- In February 1924, Hsieh compiled An Overview of Northwest Mineral Resources, which discussed the petroleum, coal, gold and copper resources in Xinjiang, Gansu, Shaanxi and Inner Mongolia in northwest China. This was the first time that Chinese geologists studied and summarized the petroleum geology in China.
- In October 1924, the first Chinese textbook *Geology (Part 1)* compiled by Hsieh was published by the Commercial Press. It was the first general geology textbook compiled by a Chinese geologist.
- On April 13, 1928, Hsieh delivered a speech entitled Geology of Chung Shan and its bearing on the supply of artesien water in Nanking at the Nanjing Society of Chinese Science. This article was revised and published in the fourth issue of Volume 13 of *Science*. It was the first work of Chinese hydrological research. In June of the same year, his article Geology of Chung Shan and its bearing on the supply of artesien water in Nanking was published in the second issue of Volume 7 of *the Bulletin of the Geological Society of China*.
- In March 1929, the first petroleum geology monograph in China, *Petroleum*, compiled by Hsieh, was included in the 14th volume, No. 161, of the Encyclopedia Series edited by Yunwu Wang and published by Shanghai Commercial Press. This is the earliest petroleum geology monograph in modern China.
- In April 1929, Hsieh published A microscopical study of some coals from Szechuan, S.W. China in Volume 8, Issue 1 of *the Bulletin of the Geological Society of China*. It was later reprinted by the British magazine *Fuel*. It was the opening and foundational work for China's coal petrology research. It was one of the research results of his visiting scholar in Germany in 1928 (Figure 5). In December of the same year, Hsieh wrote Geological and microscopical study of some copper deposits of China based on another result of his research in Germany, which was published in Volume 8, Issue 4 of the *Bulletin* of *the*

Geological Society of China. It pioneered the study of mineragraphy in China. The attached microphotographs were first cited by the well-known German mineralogist and ore deposit geologist H. Schneiderhohn (1887-1962) in his *Mineragraphy Course*, and then introduced by German mineralogist and petrologist Ramdohr Paul (1890-1985) in his professional masterpiece *Mineragraphy Course*.

Figure 5. Hsieh’s passport photo in August 1928 when he went to Germany as a visiting scholar

- In July 1930, the Soil Research Laboratory of the Geological Survey of China was established. In the same month, Hsieh and Longqing Chang went to southern Shaanxi and northern Hebei to conduct soil geological surveys. This was the first time that Chinese geologists conducted soil geological surveys and research.
- In October 1930, Hsieh published articles entitled Some new methods in coal petrography and A preliminary petrographical study of the Peipiao coals in Volume 9, Issue 3 of *the Bulletin of the Geological Society of China*. It was also listed as the first and second issues of *the Special Report on Fuel Research*.
- On January 10, 1931, at the 25th meeting of the Geological Survey of China, Hsieh first gave a speech on soil research, classification and investigation. In March of the same year, Hsieh's article entitled *Soil Classification and Soil Investigation* and *Report on Soil Reconnaissance in San-ho, Ping-Ku and Chi-Hsien Area, Hebei Province* co-authored by him and Long Ching Ch’ang (L. C. Ch’ang) were published in the second issue of *Soil Special Report* jointly sponsored by the Geological Survey of China and the Institute of Geology of the Peking Academy of Sciences. Among them, the article entitled Soil Classification and Soil Survey is the first soil science paper written by a Chinese geologist, and Report on Soil Reconnaissance in San-ho, Ping-Ku and Chi-Hsien Area, Hebei Province is the first soil survey report written by Chinese people.
- The exploration's drilling network was used for the first time in China to conduct exploration of the Huainan coal mines in Anhui Province.

- In February 1948, Hsieh organized and initiated geological research on uranium and thorium deposits in Guangxi, China. On May 19 of the same year, he was invited to give a speech at the School of Engineering of Wuhan University entitled How to Explore Radioactive Minerals Such as Uranium and Thorium, and mentioned in his speech that China has discovered several uranium deposits. Later in the same month, he completed the Brief Report on the Uranium showing in Huangqiangping, Zhongshan County, Guangxi, which was the 73rd in the series of *Provisional Reports of the Mineral Exploration Bureau*. In July of the same year, he published the article A Brief Introduction to Uranium deposits in the 89th issue of *Mineral Exploration Newsletter*, which outlined the main minerals of metallic uranium and how to detect and identify them. It also discussed the exploration methods of uranium deposits, the world's uranium geology and mining at that time, and the application of uranium. It is the earliest document that introduced uranium deposit knowledge in detail in China, "the starting point of China's uranium deposit geological research", thus opening the prelude to China's uranium deposit geological research, exploration and development.

It is worth mentioning that Hsieh was also the first Chinese geologist to advocate the use of geological theory to prospect for minerals. He actively promoted the application of metallogenic theory, advocated the use of geological theory for mineralization prediction, and used comprehensive methods and multiple means for geological exploration and mineral survey. It must be said that Hsieh had profound theoretical knowledge and rich field practice experience in almost all minerals and mineral species, and personally discovered or guided the discovery of many mineral deposits in China.

Figure 6. In July 1932, Hsieh was in the Northern Shaanxi Oil Exploration Brigade
(Hsieh is the first from the left)

3 Fruitful mineral prospecting results and excellent management capabilities

So far, Mr. Hsieh has been a unique all-round geologist in the Chinese geological community. His research fields include general geology, regional geology, stratigraphy, structural geology, geotectonics, mineralogy, petrology, paleontology, meteorite science, hydrogeology and engineering geology, seismology, lithofacies and paleogeography, physiography and geomorphology, pedology, coal petrology, coal geology, petroleum geology, mineralogy, mineral deposits, economic geology, core drilling, geophysics, geochemistry, prospecting and exploration geology, and geological technology management, etc. Hsieh has conducted in-depth research or application in all the above disciplines and has achieved remarkable and great achievements. In many aspects, he has occupied a pioneering position in China geological community. He is a well-deserved pioneer and founder of modern Chinese earth sciences.

During his lifetime, Hsieh personally explored, studied and guided the exploration and research of a wide range of mineral resources, such as fuel, ferrous metals, non-ferrous metals, rare metals, rare earth metals, precious metals, important non-metallic minerals and water resources, etc. Specifically, he involved coal, oil, natural gas, iron, manganese, aluminum, copper, lead, zinc, tungsten, tin, antimony, gold, mercury, silver, rare earth metals, cement raw materials, refractory clay, clay, graphite, bentonite, vermiculite, groundwater and other mineral deposits of different genetic types, such as sedimentation, contact metamorphism, regional metamorphism, magma differentiation, magmatic hydrothermal, hot water, weathering and leaching, and residual slope accumulation.

Figure 7. A group photo of some colleagues from the Mineral Exploration Bureau in front of the Li Family Ancestral Hall in Zhaotong, Yunnan on November 5, 1941

(At that time, Hsieh, who is in the middle of the first row, had just returned from Xiangyun in western Yunnan after completing a geological survey)

In addition to personally conducting or directing geological research, Hsieh also has outstanding organizational and management skills and the wisdom to operate a mining company.

In order to raise foreign exchange to meet the country's needs for anti-Japanese war and to support the war with practical actions, on May 11, 1939 during World War II, Hsieh left his comfortable teaching and geological survey positions and founded the Jianghua Mining Bureau in the wild land of Hunan Province, the rear area of the Anti-Japanese War, and served as the general manager. During this period, he established the only mining site in Hunan at that time that used machines to mine placer tin deposits, which strongly supported China's great anti-Japanese war.

On May 15, 1940, after the Jianghua Mining Bureau entered normal production, Hsieh went to Yunnan to prepare for the establishment of the Mineral Prospecting Engineering Office along the Xufu (Yibin)-Kunming Railway (Xu-Kun Railway) and served as the Engineer in Chief of the office. On October 11 of the same year, the Southwest Mineral Exploration Bureau (SMEB) was established, and Hsieh served as the director. At this time, since most of northern, eastern and even central China had fallen into the hands of the Japanese army, the southwest became China's rear area. During this period, Hsieh led the SMEB with only a few dozen people, in the harsh environment of remote and poor villages with high mountains and dense forests, bandits and occasional bombings by Japanese fighter planes, in many areas including today's Yunnan, Sichuan, Guizhou, Chongqing, Hunan and Guangxi Provinces, and investigated the coal, iron, copper, lead, silver and tin deposits and other mineral resources and related geological and geographical settings in this area, and also investigated and discovered bauxite and rich aluminum deposits in Guizhou and Yunnan Provinces. At the same time, he also wrote and published many investigation reports and research articles on the geology and mineral deposits of the area in his busy schedule. On October 1, 1942, the SMEB was renamed the Mineral Exploration Bureau (MEB).

As a result, Hsieh became a pioneer in China's geological and mineral exploration and one of the earliest geological technology managers.

On April 25, 1946, after the victory of the Chinese War of Resistance Against Japanese Aggression, Hsieh assigned C. C. Chang and Shuo-Hai Huo to conduct geological surveys of uranium mineralization at Huangqiangping in Zhongshan，Guangxi using trenching exploration. On October 6 of the same year, the new coalfield of Bagongshan in Huainan, Anhui was discovered through drilling. The borehole was located by Hsieh in September of that year. Later, the new coalfield in Huainan became one of the eight major coal bases in China and the most important coalfield in East China. On October 28 of the same year, Hsieh announced at the second paper symposium of the 22nd Annual Meeting of the Geological Society of China held in Nanjing that the Geiger-Muller Counter made by Zonghuang Zhang, director of the Geophysics Prospecting Section, MEB, had been initially successfully developed. On November 22 of the same year, Hsieh sent Zonghuang Zhang to Nanjing with the Geiger Muller Counter made by Zhang to test uranium ores mined from Nanling in South China and Northeast China. On the morning of December 1 of the same year, Hsieh presided over the first popular science lecture held by the MEB in the auditorium of the Science Museum of the China Central University in Nanjing. The title of the lecture was The Method of Identifying Radioactive Minerals Using the Geiger-Muller Counter, and he introduced the Geiger-Muller Counter made by Zonghuang

Zhang. On December 25 of the same year, Hsieh delivered a speech entitled How to Discover New Coal Fields and further emphasized the use of geological theory to guide mineral prospecting: “As long as we can conduct planned drilling according to geological principles, the key to this natural treasure house will eventually be obtained by us. The days of finding minerals by tracing old mining relics are over.” On May 16 of the following year, Hsieh published an article titled Discovery of the New Coalfield in Huainan in Shanghai's *Ta Kung Pao,* saying: "The discovery of the new coalfield in Huainan was based on many theoretical deductions and inferences in paleogeography, stratigraphy, and structural geology; in other words, it was the result of pure geological theory coupled with drilling."

Figure 8. Group photo of the 12th anniversary of the founding of the Academia Sinica of the Republic of China and the first academician conference in April 1948
(The 2nd from the left in the 4th row is Hsieh)

On February 17, 1947, Hsieh predicted that there would be phosphate mineralization in Chuxian and Bengbu, Anhui, and sent K. W. Sha, T. M. Han and others to investigate. As expected, a phosphate layer extending for thousands of meters was found in the Wutai system. In February of the same year, Hsieh published an article entitled New Trends in China's Economic Geology in the 1st and 2nd issues of *Geological Review*, which summarized the development of China's economic geology for the first time and divided it into three periods: the initial survey period, the period of theoretical research, and the period of new trends. In late March of the same year, the Fengtai phosphate deposit in Anhui was discovered. In the same month of the same year, Bentan Wang and Cunli Gao were sent to the Xisha Islands to investigate phosphate deposits with the investigation team organized by the Navy Department, and Hsieh himself went to the Xisha Islands for a field investigation on the 12th of the same month. Also in March of the same year, Hsieh published an article titled Chatting about Crystal Deposits in the *Mineral Exploration*

Newsletter and pointed out that crystal was "listed as one of the war minerals during World War II, and the warring countries searched for it everywhere. Our country also sent geologists to search for it, but except for a small amount of production in Tianyang, Guangxi, no large deposit has been found. In the future, there may be a possibility of discovering huge amounts of crystals in Donghai county, northern Jiangsu, and/or various parts of Shandong". A few years later, Donghai, Jiangsu became China's most famous crystal producing area and crystal city, completely fulfilling Hsieh's prediction. On April 7, Hsieh speculated that there was potential for phosphate mineralization in the Jiangsu and Anhui Provinces, so he sent Nanting Dong and T. M. Han to Luhe in northern Jiangsu for an on-site investigation. As expected, they discovered the Tertiary phosphorus-containing layer near Beibanqiao. On the 20th of the same month, Hsieh and others discovered a Tertiary phosphorus-bearing layer in the Fangshan area of Luhe, Jiangsu Province. In May of the same year, Hsieh published an article titled Gibbsite bauxite deposit discovered by the MEB in the 75th issue of *Mineral Exploration Newsletter*, announcing the discovery of Gibbsite bauxite deposit in Zhangpu, Fujian Province. In early July, Hsieh discovered multiple layers of siderite and bauxite shale while observing the drill core of the Huainan New Coalfield on site. In November of the same year, Hsieh completed the article titled *Some promising regions for searching uranium and thorium deposits in China*, which identified seven prospecting regions for uranium-thorium deposits in China. A world-class uranium deposit discovered in China later is located in the first uranium prospecting region identified by Hsieh, namely the Pegmatite veins in the Precambrian basement. As of 2011, 74% of the proven uranium reserves in China came from the second prospecting region identified by Hsieh. On December 6 of the same year, Hsieh attended the first petroleum geology symposium in Chinese history, namely the Sichuan Petroleum Geology Symposium held by the MEB, and expressed seven opinions on Sichuan petroleum geology.

In April 1948, Hsieh sent personnel to investigate the uranium-thorium deposits in Guangxi. In March, he personally went to Guangxi to investigate the Huangqiangping uranium mineral showing and believed that it was worth drilling in the future. In September of the same year, he discovered the Qixiashan lead deposit in the suburbs of Nanjing. In October of the same year, Hsieh read out the article entitled On oil exploration in the Region South of the Yangtze River, criticizing the argument of "China has no oil", and for the first time clearly criticized the "theory that oil is only in the Northwest China", clearly pointing out that China must have oil, and it is not necessarily limited to the northwest. He first pointed out that Heilongjiang Province in the northeast China has oil. In December of this year, China's cultural giant and scholar Hu Shih mobilized Hsieh to go to south to Taiwan, but Hsieh declined. In the same year, Hsieh organized seven drilling teams to operate 16 drilling rigs in seven mining areas in five provinces, including Anhui, Hunan, Guangxi, Hubei and Taiwan, to explore for various minerals and discovered the Qixia lead deposit and the Xiashu molybdenum deposit.

In June 1949, Hsieh formulated the 1950 China Uranium Exploration Plan, planning to send 15 people to the uranium mineralization prospecting areas he had identified, such as Heilongjiang, East Liaoning, Taiwan and Guangxi, to conduct uranium-thorium ore exploration, detailed investigation or drilling.

After 1949, Hsieh discovered the Qixiashan lead-zinc-silver-manganese deposit in the suburbs of Nanjing, and guided the discovery of the Baiyinchang copper-lead-zinc polymetallic deposit in Gansu.

In 1954, Hsieh wrote the article titled Notes on uranium-thorium ore prospecting to provide further specific guidance for China's uranium prospecting work. There is no doubt that Hsieh is the pioneer and founder of China's uranium-thorium geology and exploration.

In 1954， Hsieh as a member of the standing committee and the engineer in chief of the Reconnaissance Committee of the Ministry of Geology published a paper titled *China's oil-producing areas and potential oil-bearing areas* which divided China’s oil-producing areas and potential oil-bearing areas into 3 categories including 20 oil-gas areas. This paper played a role of programmatic literature of petroleum and natural gas reconnaissance in China in the 1950s, he defined the target areas for oil exploration, enabling China to achieve a major breakthrough in oil exploration and discover world-class oil fields such as Daqing and Shengli, completely removing the label or fallacy of "oil-poor" in China.

In short, as he himself very objectively evaluated, Hsieh is an all-round geologist who has received rigorous geological training.

Figure 9. Hsieh and his wife took a group photo in November 1947 when they attended the 23rd Annual Meeting of the Geological Society of China in Taiwan, China

(Hsieh delivered a speech at the conference titled Palaeogeography as a guide to mineral exploration)

4 Teaching and educating people, with students all over the world

In terms of geological education in China, Hsieh's students are spread across different regions of China. Before 1949, he served as a professor of geology and dean of geology departments at several top universities in China. During the period of 1924-1927, he served as a professor of geology at Peking University. In July 1927, he was sent to Sun Yat-sen University in Guangzhou to participate in the establishment of the Guangdong-Guangxi Geological Survey and carried out the first field geological survey in Guangdong Province.

Figure 10. Department of Geology, Peking University, bids farewell to the graduating class of 1937 (The person in the front row wearing a black veil is Hsieh, whose mother had just passed away)

In February 1928, Hsieh left Guangzhou and arrived in Nanjing, the capital of China at that time, to teach at the Department of Geology of the then China Central University. During this period, he investigated the geology of the Zhongshan Mountain in Nanjing and its relationship with the water supply of Nanjing city, pioneering the study of the geology of urban water supply in China.

In May 1930, Hsieh returned to China after having worked in coal petrology and mineragraphy for nearly two years in Germany and France. Together with his mentor Wong, Hsieh founded China's first soil research laboratory, carried out China's first soil survey, and published the first systematic soil research paper. In October of the same year, the Qinyuan Fuel Research Laboratory of the Geological Survey was established, with Hsieh as the director. Hsieh first introduced polarizing microscopes into coal petrology research, and published papers such as *Microscopic research on domestic coal* and *Some new methods of coal petrography,* which attracted the attention of the international geological community. Early coal petrology researchers from France, the United States, the United Kingdom, Germany and other countries wrote to request relevant papers, thus establishing Hsieh's status as one of the world's coal petrology pioneers and the founder of China's coal petrology.

In 1936, Hsieh published *On the Late Mesozoic-Early Tertiary Orogenesis and Vulkanism, and Their Relation to the Formation of Metallic Deposits in China,* based on Wong's previous *Theory* *of Mineral Regions of China* and *The Age of Mineral Deposits in China,* advanced Chinese metallogeny by a great step forward.

Shortly after 1949, Hsieh founded the Nanjing Geological and Mineral Exploration School and served as the director and professor of the school affairs committee. In a short period of time, the school trained 110 geological personnel of various types that were urgently needed at the time, equivalent to more than one-third of all geological personnel in China at the time. It provided a vital force for China's mining development.

After 1949, nearly half of the backbones in charge of geological technology in the geological departments of provinces and regions across China, including geologist-in-chief, were Hsieh's students. In addition, the backbones of geological technology in the Ministries of Petroleum, Metallurgy, Coal and Nuclear Industry of China were also his students. At the same time, Hsieh served as the deputy director of the China Geological Work Planning Steering Committee of the People's Republic of China and the director of the Planning Department. He actively participated in the geological work plan after the founding of the People's Republic of China, especially the deployment of exploration in key mining areas. He mobilized Y. C. Cheng, K. Y. Yen, Y. L. Wang, C. H. Lu, W. K. Kuo, S. H. Sung, C. Wang and C. Y. Lee, who served as the geologists-in-chief of the most important mines in China at that time, namely Hubei Daye Iron Mine, Inner Mongolia Bayan Obo Iron Mine, Hebei Pangjiabu Iron Mine, Guizhou Guanyinshan Iron Mine, Gansu Baiyinchang Copper Mine, Shanxi Zhongtiaoshan Copper Mine and Shaanxi Weibei Coal Mine, which played a decisive role in China's successful completion of the mineral exploration tasks of the first and second "Five-Year Plans" that year. Later, most of these geologists-in-chief became academicians of the Chinese Academy of Sciences and the backbones of geological technology in China.

Figure 11. In 1950, Hsieh and his wife Jingnong Wu took a group photo with their eldest son Xuejing Xie and his wife, their third son Xuefang Xie, and their youngest son Xuezheng Xie

5 What his teachers, colleagues and students say about Hsieh?

In 1924, Mr. V. K. Ting, the founder of Chinese geology and Hsieh's mentor, wrote in the preface to the textbook *Geology (Part 1)* compiled by Hsieh: "Mr. Hsieh is the most hardworking young man in the Chinese geological community. He has never taught so far, but since 1916, except for the three years he studied in the United States, he has spent four months every year studying geology in the field." Ting also said that Hsieh "is fond of reading and writing, so this textbook he wrote... is well-organized and well-ordered. The examples he cited are all Chinese facts, such as the causes of earthquakes, the distribution of minerals, and the changes in rivers. They all incorporate recent research to arouse readers' interest. It can only be regarded as a pioneering work among textbooks..."

In 1934, when Wong, then director of the Geological Survey of China, was in danger of death after a car accident, Ting wrote worriedly: "If Wong does not survive... we should not send anyone to be the director of the Geological Survey. I personally believe that Mr. Hsieh (now a professor of geology at Peking University) is the most qualified and can serve as acting director of the Geological Survey if necessary."

In 1947, Hsieh's student C. Y. Li wrote in his article entitled Mr. Hsieh and China's mineral exploration: "The promotion of national mineral exploration began with the establishment of the Mineral Exploration Bureau. Up to now, this is still the only institution, whether public or private. And this institution has been presided over by Mr. Hsieh since its establishment, which is really a cause for celebration... Mr. Hsieh is so hard working that he really can't put down his books." When talking about the position of director of the MEB, Li said that most geologists then are pedantic nerds and are not qualified for this scientific and technological management position. "We are close to being pedantic because we cannot put aside books. It is actually difficult to find such workers, and it is even more difficult to find a director of such an organization." He went on to write: "Mr. Hsieh is undoubtedly a very suitable candidate. Mr. Hsieh has made great achievements in academics. He has hosted lectures at several national universities, served in the Geological Survey of China, traveled to many places, visited many mines, and was responsible for running mines himself. He was in charge of the MEB from the Mineral Prospecting Engineering Office along the Xu-Kun Railway. He is experienced. The mineral exploration business is gradually valued in China today, and Mr. Hsieh's contribution cannot be erased”.

In the same month of the same year, Y. T. Nan wrote an article summarizing Mr. Hsieh: "The sun is shining brightly in the sky, and he has been drinking for fifty years. He has accumulated billions of pearls and has educated thousands of students. He is a man of extraordinary talent and swiftness, and he is a man of great skill when slaying a dragon. How can one look up to the mountains? He is a wise man in the world. The fortunes and the winds and clouds are together, and the good luck has come over the years. He is the key figure to success, and he has a keen eye for excellence. He has developed aluminum, copper, and tin in Yunnan and Guangxi Provinces;

and phosphorus, iron, and coal in Jiangsu and Anhui Provinces. The career will last for generations, so I'll toast to your happiness with two or three glasses. Nan went on to explain this congratulatory message, which has a strong Chinese ancient style and is therefore difficult to translate into other languages: Mr. Hsieh "once encouraged me with the words 'one should not live in vain', which shows that he is a man who is willing to work hard. With his persistence in his post and hard work for more than 30 years, his so-called genius has been brilliantly exerted. His great achievements and numerous publications really make people sigh that no one can catch up with him. For all mineral issues such as coal, iron, tin, copper, aluminum, oil, gas, salt and phosphorus, he has written extensive, rigorous and insightful articles, which have benefited people a lot... In less than two years after we returned to the capital Nanjing after the victory of the Anti-Japanese War, based on the relationship between Chinese paleogeography and mineral deposits, Hsieh discovered the Huainan coalfield, the phosphate deposits in northern Anhui, and the gibbsite deposit in southern Fujian. This can only be said to be the reward and achievement he has achieved for his persistence in his post over the years." "When Mr. Hsieh was the director of the Rock and Mineral Research Laboratory at the Peking Geological Survey, the academic research atmosphere in the institute was the strongest."

At the same time, Hsieh's student C.C. Chang concluded in the article titled Teacher Hsieh's Contribution and Success in Applied Geology: "The development of China's geology has only been in the past thirty years. During this period, although three or four hundred people have studied geology, there are still not many who actually work in this field. As for the current geological institutions and mines in various places, the number of people doing field work and concentrating on research is less than one-third of the total. Most people are forced by life or limited by physical strength, and some are unwilling to endure hardship, so they abandon their own geology major and do work that is not what they learned. Among these more than one hundred actual workers, those who specialize in applied geology are probably less than one-third. Given China's vast territory, abundant mineral resources, and the number of places that urgently need to be surveyed and developed, these dozens of applied geologists are really too few. After the long Sino-Japanese War and the continued turmoil in China after the victory... People who work in geology have a sense of 'no tomorrow'. Therefore, many geologists have abandoned their jobs and changed their careers. It is rare to be able to make geological work a lifelong career. The person who has been engaged in applied geological research for 30 years is Mr. Hsieh, who led us in mineral exploration. I remember that fourteen years ago, when Mr. Hsieh was a lecturer hired by the Chinese Culture Foundation at the Department of Geology of Peking University, he worked in the Geological Survey of China except for teaching... Mr. Hsieh has always worked hard for the geology institute, but he does not receive subsidies or allowances from the survey institute, and he often voluntarily leads a team to go out for investigation every spring and autumn. This is worthy of our admiration. Mr. Hsieh has served as a geological instructor in Peking University, Tsinghua University, Peking Normal University, and Sun Yat-sen University, and has produced many disciples who continue to work hard for applied geology.

Most of them can now conduct independent research, and some can even train younger generations to do field work. This is Hsieh’s harvest in geological education over the years, which is also his indirect contribution to applied geology. "

B. C. Yang described Hsieh's spare time in the article entitled Miscellaneous memories of teacher Hsieh's work and life in the past seven years published in the same period: "Except for working eight hours per day in the office, the teacher mostly reads books in the evening. In addition to smoking and drinking tea, he occasionally takes his family to see one or two movies, and never attends dances. Teacher Hsieh's writing skills are rare. His speed, detailed insights, and expertise are especially outstanding. In addition to English, French, and German, he also learned Russian from our colleague Da-Nien Yeh in 1943. When our office was in Chongqing in 1944 and 1945, Teacher Hsieh attended the Russian class of National Central University until he reached the level of listening and reading ability. This kind of hard work and perseverance is truly admirable and worth emulating."

Hu Shih commented on the graduates of the Institute of Geology in 1956: "This Institute of Geology was founded in the third year of the Republic of China and ended in the fifth year of the Republic of China. The Graduates were responsible for survey work in various places at the Geological Survey. The best students were gradually selected to study abroad. Many leading talents in the Chinese geological community, such as Chia Yung Hsieh, C. C. Wang, L. F. Yih, C. Li, H. C. T’an, T. O. Chu, and H. T. Lee, all graduated from the Institute of Geology."

In 1989, H. Chu, academician of the Chinese Academy of Sciences, commented: "Mr. Hsieh is such a geologist: he never despises intuitive empirical evidence, but pays more attention to speculative rationality. He is good at microscopic examination, but never ignores the macroscopic whole. He constantly pursues the dynamic research of the system from discrete static analysis. He is good at seeing the big picture from the small details, and never misses any new ideas. At the same time, he firmly and persistently stares at the future and thinks about the long term. He has devoted his life to the development of China's mineral resources, and has always been fighting at the forefront of geological science thought."

On the centenary of Hsieh's birth in 1997, Chingchang Biq, who later became the director of the Geological Survey of Taiwan, commented on Hsieh: "China has had geology for about 90 years. In the first 40 to 50 years, Hsieh was the first true scholar who made direct, concrete, and multi-faceted contributions to Chinese geological studies."

In 1998, Y. C. Cheng, one of Hsieh's students，an academician of the Chinese Academy of Sciences, wrote: "Teacher Hsieh is a master of geology, a good teacher and mentor to me, and the enlightenment mentor of my 60-year geological career! His academic achievements, scientific and technological achievements, his contributions to the motherland and even the entire geological science and technology, and his great achievements in the establishment of my country's geological cause will be recorded in history forever! His hard-working spirit for the cause of science and technology will always be a role model for future generations to learn from!"

The late academician of the Chinese Academy of Sciences and well-known geologist Shu Sun once sincerely pointed out: "The Chinese geological community owes Mr. Hsieh justice and has not given him enough recognition."

The author of this book, Prof. Lisheng Zhang, praised Mr. Hsieh as: a well-known economic geologist and mineralogist at home and abroad, the main founder of China's mineral geology, the founder of China's mineragraphy, the pioneer and one of the founders of China's coalfield geology, one of the pioneers of world coal petrology and the founder of China's coal petrology, a pioneer of China's petrology, an advocate of the theory of terrestrial oil generation, the pioneer and one of the founders of China's soil science, a pioneer in China's modern meteorite research, one of the pioneers of China's hydrogeology and engineering geology and China's geomorphology and physiography, a pioneer and founder of China's mineral exploration, a pioneer of economic geology in China, a pioneer and advocate of China's geological drilling business, the main instructor of China's petroleum survey in the 1950s, a great contributor to the discovery of China's Daqing oil fields and other oil discoveries and the geologist and economic geologist who has discovered the most mineral deposits in China to date.

In January 2024, Guangbo Song, an expert on the history of Chinese geological sciences, commented on Mr. Hsieh after reading this book: "In many academic fields, he is either a pioneer or a leader, which is unique in the Chinese geological community. Hsieh is also an outstanding geological educator and scientific organizer. His talent in scientific organization is no less than that of his teachers V. K. Ting and W. H. Wong. He is also a pioneering figure who can create institutions and academics out of nothing. By the 1930s, he had become a leader in his own right. He served as the director of the Department of Geology of Peking University, Tsinghua University, and Peking Normal University, the acting director of the Geological Survey of China, and the director of the Peking Branch of the Geological Survey of China." "C. Y. Hsieh has made great contributions to China's geological cause, has a very high status, and has a far-reaching and profound influence. However, for a long time, he has not received enough attention and evaluation. For decades, he has not been ‘fully affirmed’ and owed ‘justice’. T. K. Huang solemnly left a message before his death: Hsieh's rehabilitation is not thorough, and his contributions are not evaluated enough. I hope the leaders will study and solve it." "In the over 110-year history of Chinese geology, the top six figures should be Ting, Wong, Hsieh, J. S. Lee, followed by C. C. Young and T. K. Huang. "During the five years of the Anti-Japanese War, the area surveyed by the MEB led by Hsieh covered the provinces of Guizhou, Yunnan, Sichuan, Xikang, Hunan, and Guangxi. The mineral geological outline map of the southwestern provinces surveyed covers an area of nearly 100,000 square kilometers. The exploration targets include coal, iron, copper, silver, lead, zinc, mercury, gold, tungsten, tin, arsenic, antimony, nickel, aluminum, petroleum, salt, porcelain clay, apatite, sulfur, saltpeter, asbestos, mica, and corundum. Some of these works were original discoveries made by Hsieh, while others were completed under Hsieh's leadership. At the same time, he accumulated successful work experience: professional organization, work planning, strict management, set time limits, expand the scale, raise funds generously, and reward discoveries as an incentive. In short, Hsieh's contribution to wartime mineral exploration is difficult for any other geoscientist to achieve, and he is the well-deserved first person in China's mineral exploration." "Hsieh led the mineral exploration business in the situation of ‘desperate and hard work’ during the War of Resistance Against Japan, serving the country with science. After the victory of the War, Hsieh was saddened by the interference that the war brought to the geological cause, and eagerly hoped that the turmoil would end as soon as possible, ‘so that we can start development to build a new, complete, prosperous and great country.’ When the war was about to come to an end in early 1949, he accepted the advice of the underground party of the Communist Party of China, gave up the plan to go abroad to attend academic conferences, stayed in Nanjing to protect the MEB, and looked forward to the victory of the Communist Party. In May, the MEB was handed over to the Military Control Commission in an intact and orderly manner. He was invited to lead a team to Shanghai to help take over the Shanghai Pseudo-Capital Committee. He also said: ‘Future geological work should be coordinated with the people's demands and the government's national policies. We should concentrate our efforts and seek truth from facts to move forward on the road of production and construction’. This is to welcome the new regime that is about to be established with full enthusiasm, and to expect the geological cause to have a great development in the new era. As for the examples that others could not come up with based on his foresight and experience and were proven correct by facts, there are countless of them, such as the discovery of the Yaerxia Oilfield in the 1950s. His contribution to the oil survey, especially the discovery of the Daqing Oilfield, is irreplaceable by anyone. Hsieh is a representative of all patriotic scientists. Long-term unfair treatment made Hsieh depressed and humiliated, until he committed suicide, and even could not get a fair evaluation after his death. But for the country, isn't it a great loss?"

Figure 12. In June 1955, Hsieh took a group photo with some members of the Xinjiang Petroleum Survey Brigade of the Ministry of Geology during his petroleum geological survey there

(The person in the middle facing the camera is Hsieh)

6 Study and research experience

On August 19, 1897, C. Y. Hsieh was born in Shanghai, a city of ever-changing dynasties. He was the first generation of geologists and scientists trained in China. In 1948, he was elected as an academician of the Academia Sinica of the Republic of China, and in 1955, he was appointed as a member of the Chinese Academy of Sciences of the People's Republic of China.

In 1913, Hsieh entered the Institute of Geology，Ministry of Industry and Commerce, which was founded by H. T. Chang and V. K. Ting, the founders of China's geological cause and geological science, to study geology. After graduating in 1916, he became an investigator of the Geological Survey of the Ministry of Agriculture and Commerce, one of the "Eighteen Arhats" in the Chinese geological community.

Due to his outstanding achievements, Hsieh was recommended by the Geological Survey of China to study in the Department of Geology at Stanford University in the United States in 1917. In 1919, he transferred to the Department of Geology at the University of Wisconsin and received a Master of Science degree from the university in 1920. On the eve of returning to China, he published a series of papers "The Outline of Mineral Deposits" in the magazine *Science*, which systematically expounded the theory and practice of mineral deposits for the first time in China, and pioneered the study of mineral deposits in China.

After returning to China in the spring of 1921, Hsieh rejoined the Geological Survey of China and immediately conducted the first real earthquake science survey in modern China, namely the "Gansu Earthquake Survey" with W. H. Wong and others. Then he immediately carried out the first real scientific petroleum geological survey nearby, and wrote the first earthquake geological survey report and the first petroleum geological survey report in China. In the winter of the same year, Hsieh and Professor P. L. Yuan proposed the establishment of the Geological Society of China. Hsieh was also ordered to draft the "Constitution of the Geological Society of China" for this purpose, and designed the emblem with his colleagues H. T. Chang, Amadeus William Grabau, and C. C. Young at the time. Hsieh also served as the first secretary of the society and the 11th and 23rd chairman of the board. At the same time, he suggested the establishment of the geological professional journal *Geological Review* and served as the editor-in-chief for many years.

In 1923, Hsieh completed the first monograph on coal geology in China, *Coal*. In the same year, he published "A Study of Chinese Meteorites" in the 8th issue of Volume 8 of *Science*, which studied the mineral composition and structure of the Daohe meteorites in Gansu, China under a microscope. This was the beginning of the study of meteorites by modern Chinese geologists. In 1924, the textbook *Geology (Part 1)* was published, which was the first general geology textbook in China. In 1925, after conducting an investigation, he and his classmate L. F. Yih studied the formation of the Three Gorges of the Yangtze River and proposed to establish three famous physiographical periods: the quasi-plane of the western Hubei period, the mature ground of the mountain plateau period and the canyon period, which was a foundational work for Chinese geomorphology and physiography.

From August 1928 to May 1930, Hsieh went to Germany and France as a visiting scholar, engaged in coal petrology and mineragraphy research, thus pioneering the research of coal petrology and mineragraphy in China.

In 1929, Hsieh published China's first petroleum geology monograph, which theoretically expounded the theory of continental origin of petroleum for the first time, discussed the possibility of oil generation from various continental sedimentary rocks, and clearly pointed out that in the delta sedimentary area, "marine and continental strata often alternate, which is most suitable for the accumulation of oil" and "the most suitable oil-producing strata are shallow sea or delta sediments."

From 1931 to 1937, Hsieh taught at the Department of Geology of Tsinghua University, Peking Normal University and Peking University, and served as a professor and the dean of the Department of Geology of each school. Many of the older generation of Chinese geologists who later became world-renowned were his students. Such as T. K. Huang, Y. C. Cheng, C. Y. Lee, H. C. Wang, T. I. Young, W. Y. Chang, C. Y. Wang, Y. H. Lu, L. T. Yeh, S. P. Tung, W. K. Kuo, C. T. Yuan, C. H. Chao, and H. J. Chu. All of these students later became academic masters in various departments and colleges in China. During this period between 1932 and 1933, as a research professor at Peking University, Hsieh went to the middle and lower reaches of the Yangtze River several times to investigate iron ore, and went to Hunan to investigate the lead-zinc mines in central Hunan. *Geology of the Iron Deposits in the Lower Yangtze Region* completed shortly thereafter divided the iron ore deposits in China into four major categories and 17 types. This book, together with *The Lead-Zinc Deposits of Central Hunan* and *The Shuikoushan Lead-Zinc Mine, Central Hunan, South China* compiled by him during this period, have become classic documents and important references for the study of related mineral deposits in China. In the autumn of 1937, due to the "July 7 Incident", Hsieh fled Peiping to the southwest anti-Japanese rear area.

During China's arduous War of Resistance against Japanese Aggression in the last century, Hsieh led the MEB and actively carried out China's mineral exploration business in the rear areas. He applied geology, geological technology and geological scientific methods to production practice, while integrating theoretical knowledge of sociology and economics, and conducting cost accounting in accordance with the laws of market economy, thus becoming a pioneer of China's mineral economics.

On December 25, 1945, Hsieh flew to Taiwan to inspect oil mines and returned to Shanghai on January 15 of the following year. On February 2, 1946, Hsieh discussed Taiwan's oil geology with American experts Ruby and Small in Shanghai. In March of the same year, Hsieh's report

No. 49, "Oil and Natural Gas in Taiwan," was completed and an abstract was published in the 61st issue of *Mineral Exploration Newsletter*.

In 1947, when Hsieh celebrated his 50th birthday, the 78th and 79th issues of *Mineral Exploration Newsletter* published a special issue to celebrate his birthday. In the "Editor's Note", it was said that Hsieh "has served the geological community for nearly 30 years, and his works are numerous and his contributions to Chinese geology are great. Several articles in this issue describe him in detail..." Among them, the article entitled Catalogue of Mr. C. Y. Hsieh's Works compiled by K. C. Tsao included a total of 178 articles (books) written by Hsieh from 1922 to July 1947.

After 1949, Hsieh summarized and published a series of research articles and monographs on coalfield geology. He made great contributions to China's coalfield geological exploration and development. He is a well-deserved pioneer of China's coalfield geology.

Since the 1940s, Hsieh had paid great attention to the investigation and research of China's petroleum geology. As early as 1948, he first pointed out that there might be oil in Heilongjiang, Northeast China. In 1949, he further pointed out that "the distribution of China's oil is by no means limited to the northwest corner", "the most important mineral that has not been discovered in the Northeast China is oil...", "From a regional perspective, our future survey work should pay special attention to North Manchuria, because North Manchuria is still a virgin land... There may be hope of discovering oil." Hsieh was the first geologist to point out China's oil search target to the Daqing area. Later, China's fruitful oil exploration results fully confirmed his prediction. In 1949, Hsieh formulated the first oil exploration plan of the People's Republic of China.

After that, as the chief engineer of the Ministry of Geology of the People's Republic of China and the member of the Standing Committee and the Engineer-in-Chief of the Reconnaissance Committee of the Ministry of Geology, Hsieh went all out to shoulder the heavy responsibility of the national oil survey. In 1954, Hsieh published "China's Oil-producing Areas and Potential Oil-bearing Areas". This article became the programmatic document for China to carry out large-scale oil surveys, laying the theoretical foundation for the strategic focus of oil exploration to shift eastward, the discovery of Daqing Oilfield, and the great oil discoveries in China that began with the discovery of Daqing Oilfield. During 1954 and 1957, Hsieh and his student T. K. Huang co-authored the *Oil Survey Instructions*.

After that, due to political reasons, Hsieh's position and status gradually declined. In addition, due to his advanced age, he focused his main energy on summarizing the mineralization laws of ore deposits and prospecting predictions, and published many related research articles and monographs. Before he was forced to commit suicide, he devoted himself to summarizing *Mineral Deposits in China*. However, he only completed the writing of the *Part Ⅰ. General* of *Mineral Deposits in China* and left the world forever with hatred.

Hsieh, who had been dealing with cold stones and wild mountains all his life, was a warm-hearted and sentimental person despite his outstanding achievements and great reputation. In June 1948, when he revisited the old place Babu in March of that year to inspect Guangxi Babu tin mine, he wrote with a lot of thoughts and sadness: "When I took a car through Baisha to the company, I saw the road of the Jianghua Mining Bureau that I supervised in the past. It is said that the culvert has been destroyed and cannot be used for traffic. I can't help but think of Shuxin Chen who died tragically in a car accident that year and Mr. Xiaopeng Yu who died in southern Jiangxi. Both Mr. Yu and Mr. Chen were geological engineers of the Jianghua Mining Bureau, and they had made many achievements in business planning. Now, the Jianghua Mining Bureau has become a relic, and the two gentlemen are also buried, and it is unbearable to look back. The vicissitudes of life are extremely sad. I respectfully write this article to commemorate them." Ten years ago, when Hsieh founded and served as the general manager of the Jianghua Mining Bureau, this was a place he often visited.

In essence, Hsieh was a pure intellectual, without any concept of politics or party in his mind. In early 1946, after the victory of the Anti-Japanese War, the Nationalist government moved back to Nanjing from Chongqing, the southwest rear area. In the office of the MEB led by him, the KMT flag was not hung, no commemoration week was held, and there was no KMT party group organization. Once, Hsieh's junior H. Chu asked Mr. Hsieh: The MEB is a subordinate agency of the KMT government's Resources Committee, but there has been no KMT organization and activities. How did you withstand it? Hsieh calmly replied: "I have always advocated concentrating on mineral exploration and research, not politics." His concept is similar to that of China's great intellectuals Hu Shih and Yinko Tschen (Yinkoh Chen) at that time. Unfortunately, except for Hu Shih who later went to Taiwan to enjoy his old age, Hsieh and Tschen, who insisted on staying in the mainland under Hu Shih's persuasion, both ended their lives tragically in the mainland. Hsieh committed suicide by taking sleeping pills on the evening of August 13, 1966. About a month later, Mrs. Hsieh committed suicide in the same way and at the same place.

Figure 13. Hsieh family portrait in 1960

7 The author of this book and his writing process

The author of this book, Professor Lisheng Zhang, is from Jianyang, Chengdu, Sichuan. He graduated from Chengdu Institute of Geology with a major in metal and non-metal geology and exploration in 1963, and obtained a master's degree in ore deposits from the Chinese Academy of Geological Sciences in 1966. From 1968 to 2002, he worked at the Chengdu Geological Survey Center of the China Geological Survey. He was a member of the International Association on the Genesis of Ore Deposits (IAGOD), a member of the Society for Geology Applied Mineral Deposits (SGA), a member of the Sichuan Translators Association, and an English editor of the *Acta Geologica Sichuan*. In November 2017, he was elected as a member of the board of directors of the Professional Committee for Research on Science and Technology Figures of the Chinese Society for the History of Science and Technology.

According to the author, in order to complete the writing of this book, his data collection team interviewed the very limited number of people who are still alive, and collected and sorted out a large amount of historical data. These materials include but are not limited to:

- **Certificates**: 23 certificates collected, including Hsieh's master's degree from the University of Wisconsin in 1920, his passport for visiting Germany in 1928, his temporary passport from the Chinese Embassy in France in 1930, his appointment letter as an academician of the Chinese Academy of Sciences in 1955, etc.

- **Journals**: 38 diaries covering the period from 1921 to 1966.

- **Paper manuscripts**: including Hsieh's Chinese and English paper manuscripts from 1930 to 1966. Among them are unpublished manuscripts and the manuscript of his last paper "Geotectonics and Ore Prospecting".

- **Notes and manuscripts**: a large number of reading notes and work notes, including Hsieh's 1956-1957 research work plan (draft) for the Institute of Geology and Mineral Resources of the Ministry of Geology, the development outline and direction of the Mineral Deposit Research Office in the three five-year plans, etc.

- **Letters**: A total of 181 letters, including 133 English letters and 33 Chinese letters from the 1930s, covering the period from 1919 to 1966.

- **Archives**: including Hsieh's registration form at the University of Wisconsin and his master's thesis entitled Origin of some metamorphic foliated rocks; relevant archives of Peking Normal University, Tsinghua University and Peking University; a large number of "Jianghua Mining Bureau Archives" preserved by the Hunan Provincial Archives, relevant archives of the Exploration Engineering Office along the Xu-Kun Railway preserved by the Yunnan Provincial

Archives, and documents and personnel archives of the Chinese Academy of Geological Sciences.

- **Works**: including the published Volumes 1-6 *Collected Works of C. Y. Hsieh*, the complete set of the physical version of the lead-printed version of *Mineral Exploration Newsletter* (only the 64th issue is missing but there is a scanned copy), the complete set of scanned copies of *the Annual Report of the MEB*, the simulated version of the 1919 *General Geology of Southeast China*, the original version of the second volume of the 1923, *The Iron Ores and Iron Industry of China*, the original version of the 1926 *General Statement on the Mining Industry (1918-1925)(Special Report of the Geological Survey of China, No. 2)*, the original version of the 1927 *Geology and Mineral Resources of S.W. Hupeh*, the original version of the 1930 *Petroleum*, and the scanned copy of the 1929 edition, etc.

- **Papers**: the original versions of many papers written by Hsieh between 1928 and 1964.

- **Photos**: a total of 364 photos of Hsieh collected during his lifetime, the earliest of which was a group photo of Hsieh and 15 of his classmates from the Institute of Geology in 1915.

- **Biography**: The 15 biographical materials collected are divided into four categories: the first is the published biographies of various scientists and the introductions of Hsieh published in some newspapers and periodicals, which focus on his academic experience. The second category is commemorative collections, including the commemorative collections of the 90th, 100th and 110th anniversaries of Hsieh's birth. The third category is the incomplete *Chronicle of C. Y. Hsieh* co-edited by the author of this book, Xuetong Li and Yuntang Pan. The fourth category is the record of Hsieh's situation in Berlin, Germany in the 1920s written by Yuanhong Hsieh, the eldest grandson of Hsieh.

- **Onsite visits**: The data collection team also visited Jianghua of Hunan, Babu of Guangxi, Huainan of Anhui, Nanjing of Jiangsu, Chongqing, Kunming and Zhaotong of Yunnan, Guiyang of Guizhou, etc., where Hsieh worked or lived during his lifetime, and collected relevant materials.

The author has devoted his life to complete this book in accordance with the basic principle of "respecting history, respecting facts, seeking truth from facts, and providing readers with truly reliable history". At the same time, in the process of exploring relevant history, he pointed out and corrected "many errors" in the various biographical materials collected above, such as Hsieh's birth date, the date he entered the University of Wisconsin, the date he went to Germany for research, whether he had investigated the Gansu earthquake, the exact date of his investigation in northern Shaanxi in the 1930s, the date he left Peiping after the "July 7 Incident", the date when the Mineral Prospecting Engineering Office along the Xu-Kun Railway was established, and so on.

Figure 14. Hsieh (left) and his colleague S. M. Meng during the Huangshan Granite Symposium in October 1965

Acknowledgements

All the pictures in this article are generously provided by Professor Lisheng Zhang, the author of this book the Chronicle. The author of this article would like to express his sincere gratitude to Professor Zhang.

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.