GEOL 589 – Advanced Topics: Geology and Economics of Industrial Minerals

Project Report

A Review of Lithium as a Critical Industrial Material and Engagement Prospects in the United States with Focus on New Mexico

Submitted by

Mark Leo-Russell
GEOL 589 §3
New Mexico Institute of Mining and Technology
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Project Report

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Abstract

Lithium. The name appears on our batteries and electronic devices. But what is Lithium? What makes this element work in our power supplies? Where does it come from and how do we get it? And, what about Lithium in the United States? In New Mexico?

Lithium is a critical mineral used in lubricants, metal alloys, medical products, ceramics and glass, and most commonly, batteries. As we move to alternative energy and electric vehicles, the uses and demand for Lithium is increasing. Global production of Lithium rose over 11-fold from 1995 to 2021 growing from 9.5 kTonnes to 106 kTonnes annually.

Lithium is the lightest of all metals. It has a single electron in its valence shell which is readily given up to form a cation in reactions. This makes it a very reactive metal that must be stored away from air and water but gives Lithium its good thermal and electrical conductivity—key properties for use in batteries.

Economically-viable deposits of Lithium occur in three major categories: in pegmatites typically as the minerals spodumene and lepidolite; in volcanic clays as hectorite, montimorillonite and bentonite; and from brine and geothermal deposits which includes solar evaporates, playa lakes, and extracted subsurface brines from petroleum and geothermal production.

In the United States, numerous Lithium mining and battery production projects are underway. Two new Lithium sources at various stages of development are at the Salton Sea in California and the Plumbago Pegmatite in Maine. At the Salton Sea a pilot plant is being built to co-produce Lithium and other materials from geothermal fluids already being used for power generation. In Maine the legal and social aspects of opening a large mine are still being addressed and no development has happened yet.

Although currently not in production in New Mexico, we accounted for about 10% of U.S. Lithium output from 1920 to 1950. Most of that production came from the Harding Pegmatite Mine in the Picuris District, Taos County. Since 1950 no Lithium has been mined in New Mexico but work is currently underway exploring sources of Lithium in the state that could be economically produced. There are several known Lithium sources from pegmatites in north-central New Mexico but these are not likely to be developed in the near future. Volcanic clays occur across many parts of the state and a few have potential for development in the near-term. The Popotosa Formation of the Rio Grande Rift has notable amounts of Lithium in its tuff layers. Diatomite and zeolite deposits in the Gila Conglomerate in the Buckhorn area near Silver City offer another potential source of Lithium. Brine and hydrothermal/geothermal deposits offer some of the best sources of Lithium and other minerals in the short term. The Lordsburg, Tularosa, and Estancia basins all have measurable amounts of Lithium that make them potential development areas.

Lithium recycling, especially of batteries, is very problematic. It is difficult and expensive and only about 1% of Lithium-ion batteries are actually recycled in the U.S. and EU compared to 99% of lead-acid batteries. A circular battery economy is needed but not yet developed.

Acknowledgements

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Thanks to the student and staff members of the Bureau's Economic Geology Team for all their hard work and contributions to geology research in New Mexico. The author would also like to acknowledge David Kasefang, Information Systems Team Lead at the Bureau of Geology, who lets me get away from our databases from time to time to do field work.

And special thanks to Dr Virginia T. McLemore for suggesting this topic and providing materials and guidance. Much of the work presented here, especially on Lithium in New Mexico, is based on her research and field work over the past several decades.

1. Introduction

This report describes my research into Lithium. At the suggestion of Dr Virgina McLemore, I examine various aspects of this critical industrial mineral including uses, sources, development, and the current Lithium-related research being done as part of various projects at the New Mexico Bureau of Geology and Mineral Resources.

The narrative is based on two presentations I recently gave on this subject. The first was a session at the recent New Mexico Geological Society's spring meeting where we focused on prospects for Lithium development in New Mexico. The second presentation given for the class assignment was a similar but focused U.S. efforts to develop Lithium, including work in New Mexico. The class presentation added a discussion of Lithium recycling.

2. Lithium Uses and Applications

Lithium, the lightest of metals, is a widely used critical industrial mineral. The USGS has classified Lithium as a critical mineral on the last several Critical Minerals lists (USGS, 2023a; USGS, 2023b). Lithium is used in lubricants, medicines, metal alloys, ceramics, glass, and most commonly, batteries.

Lithium greases are the most common of grease lubricants accounting for more than 75% of all such lubricants across all industries worldwide (Grease Monkey, 2019). Lithium in medications is used to treat various psychiatric conditions such as bipolar disorder and depression (drugs.com, n.d.). In metallurgy Lithium is alloyed with aluminium to produce lighter materials used in the aerospace industry. The final version of the external fuel tank for the space shuttles was principally made of Al-Li 2195 alloy (NASA, 2005). Lithium-copper is a deoxidizer used in copper casting (Belmont Metals, n.d.; Belmont Metals, 2019). In glass and ceramics Lithium reduces thermal expansion and increases durability, characteristics that make it ideal for glass stove tops (Ultra Lithium, 2018; LevertonHELM, n.d.). A specific Lithium ceramic, lithium disilicate, is widely used in restorative dentistry for crowns, caps and fillings (Giordano, 2022; Colgate, 2023).

The most widely known use of Lithium is in power storage systems, specifically Lithium-based batteries. There are numerous battery chemistries that utilize Lithium but the most common are Lithium metal (non-rechargeable) and Lithium-ion (rechargeable) batteries (EPA, 2023). The latter type is widely used in electronic devices and electric vehicles (EVs) and gets the most media coverage, especially in the context of technologies for the *green economy*.

The proportion of Lithium going to different applications has changed over time notably in the last 10 years or so. In 2010 a little less than one-quarter of produced Lithium went to manufacture batteries. By 2021 that fraction had increased to almost three-quarters of all Lithium being used in batteries and power systems (Bhutada, 2023). Figure 1 shows the changes in Lithium use in 2010 compared to 2021.

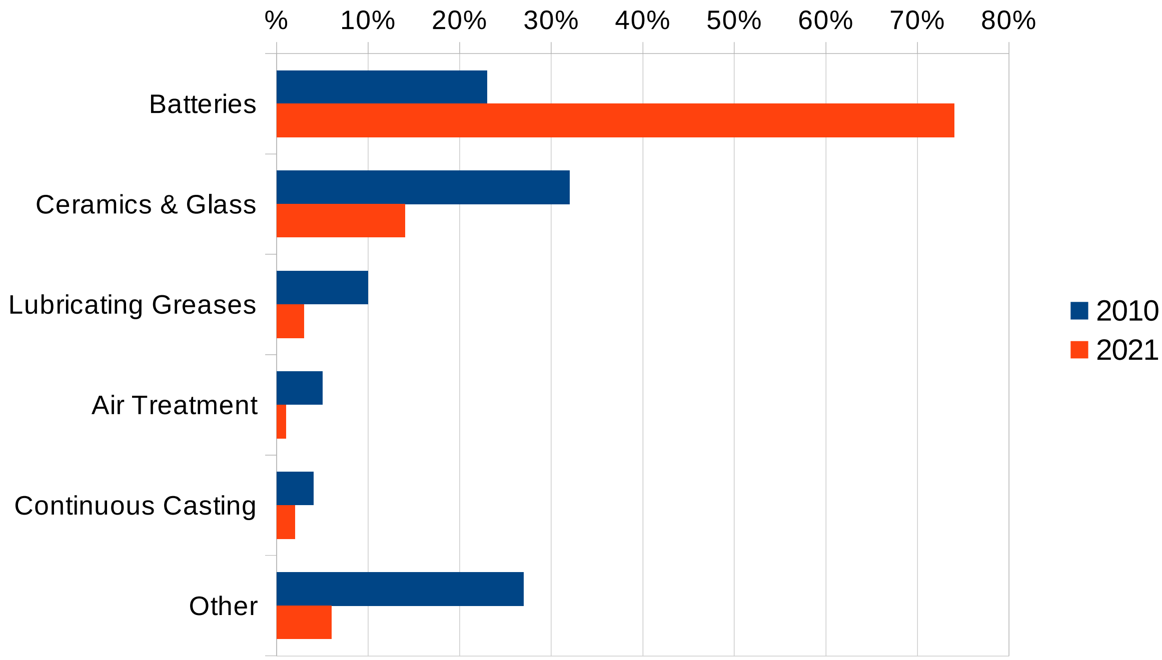

Figure 1: Comparison of Lithium end-uses from 2010 to 2021. The consumption of Lithium in batteries has increased by a factor of three over the 11 year time period (data from Bhutada, 2023).

3. Lithium the Element

Lithium is the lightest of metals with atomic number 3 and atomic weight of 6.942 amu. As an element it was discovered in 1817 by Swedish chemist Johan August Arfwedson in the mineral petalite (Dye, 2023). There are two stable isotopes of Lithium: ^{7}Li which is over 95% of natural abundance while ^{6}Li accounts for less than five percent of abundance. Lithium has a single electron in its valence shell which makes it very reactive. Special precautions must be taken in handling Lithium metal especially storing it away from air and water, usually immersed in mineral oil (Livent, 2022). This extreme reactivity gives this element good thermal and electrical conductivity—key properties for use in batteries.

The crustal abundance of Lithium is 20-70 ppm by weight. It is usually found in granites, typically granitic pegmatites. While it is found and extracted from subsurface brines, its concentration is seawater is extremely low at just 0.1 ppm (Dye, 2023).

4. Lithium the Commodity

Lithium as a commodity had a significant rise in production and trading after World War II. Annual global production averaged about 5000 tonnes between 1955 and 1980 (Bhutada, 2022). Lithium production really took off in the 1980s and had a further substantial increase in production in the mid 1990s. From 1995 to 2010 production went up from 9500 tonnes annually to 28,000 tonnes. Recently, production more than doubled from 40,000 to 86,300 tonnes in the period 2016 to 2020 (Bhutada, 2022). In the last couple of years, despite the global pandemic, Lithium production was over 105,000 tonnes in 2021 (Bhutada, 2023). Figure 2 illustrates this production history.

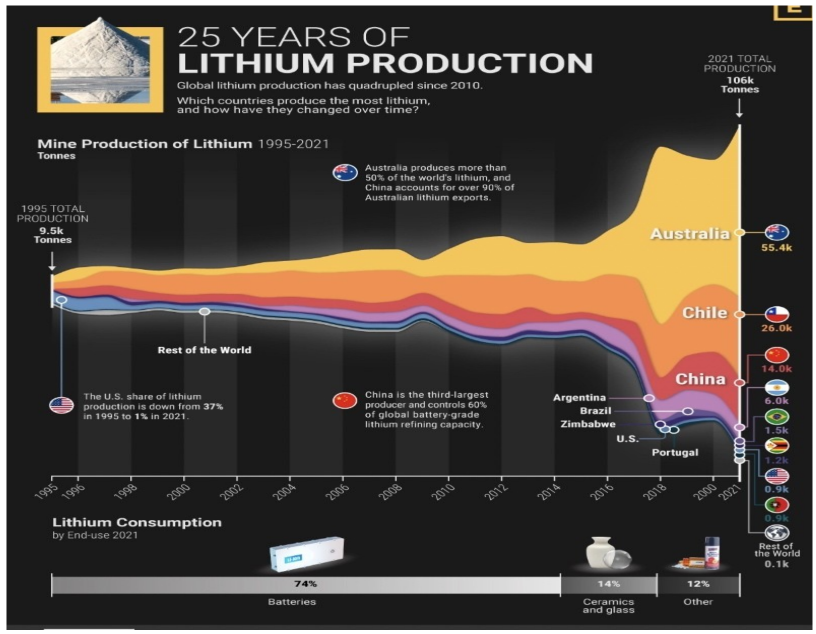

Figure 2: Global mine production of Lithium from 1995 to 2021 by producing country. Australia, Chile and China are the largest producers. In 2021 the U.S. ranked 8th among countries producing Lithium. The bottom portion of this illustration shows the uses of Lithium with almost 75% going to batteries (World Economic Forum data from Bhutada, 2023).

As a commodity traded on global markets the price of Lithium changes with economic conditions and investor whims. In July 2017 a tonne of Lithium cost ~US$20,000. By 2022 the trade price has increased almost 4-fold to over US$80,000. Earlier this year the price dropped dramatically and Lithium trades today (May 2023) at ~US$28,500 per tonne (about US$12.90/pound) (Daily Metal Prices, 2023).

Figure 3 on the next page shows the market value of Lithium from mid 2017 through today. The price was fairly stable from 2017 to mid 2021 when it increase by a factor of almost 7 times. Through most of 2022 and into early 2023 the price stayed high between US$70,000 and 80,000 per tonne.

The fall in price earlier this year is attributed to a sharp decrease in demand for Chinese electric vehicles (subsidies ended) and increasing supply from China, Australia and Chile.

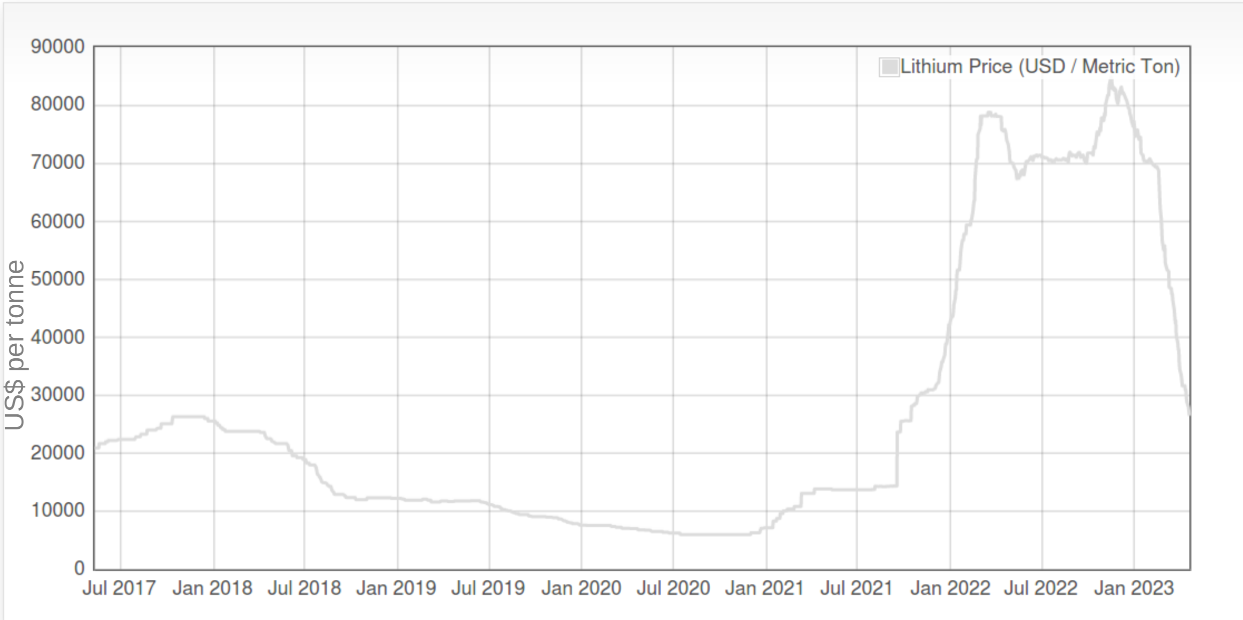

Figure 3: Market history of Lithium prices from July 2017 to first quarter 2023 (priced in US dollars per tonne). Note substantial price drop in early 2023 (Daily Metal Prices, 2023).

5. Lithium Sources

There are three main economically-viable types of Lithium deposits: 1) peralkaline and peraluminous pegmatites, 2) volcanic clays containing Li-rich hectorite, and 3) brines which include evaporates, playas and subsurface fluids from petroleum and geothermal production (Kesler, et al., 2012 and Bowell, et al., 2020 as cited in McLemore, 2021).

5.1. Pegmatites

Pegmatites are intrusive volcanic systems where conditions allow the formation of extremely large intergrown crystals. Most pegmatites have silicic composition seminar to granite but intermediate composition and mafic pegmatites are known but are relatively rare. Historically, most Lithium production was from such deposits although evaporates have become more prevalent in recent years (McLemore, 2021).

In pegmatites the primary Lithium-bearing minerals are Spodumene [$LiAlSi_2O_6$] and Lepidolite [$K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$] (mindat.org, n.d.(a,b)). Figure 4 on the next page shows typical pegmatite specimens of these two minerals.

Figure 4. Pegmatite Lithium minerals: Spodumene from the Newry Mica Mine, Oxford Co., Maine (left) and Lepidolite on Quartz from the Harding Pegmatite Mine, Taos Co., New Mexico (right) (photos: Dakota Matrix Minerals, 2023).

Globally, Lithium is currently produced from pegmatite deposits in Australia (Greenbushes (the world's largest spodumene deposit), Yilgarn and Pilbara regions, and the Grants lithium deposit); Cinovec, Czech Republic; several deposits in Canada (James Bay, Quebec Lithium and Whabouchi); and two deposits in Zimbabwe (Karrech, et al., 2019).

5.2. Volcanic Clays

Volcanic clays, usually in ancient closed basins, are another type of Lithium deposit. Here the Lithium-bearing minerals are Hectorite [Na0.33(Mg,Li)3Si4O10(F,OH)2], Montmorillonite [$(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$], and Bentonite clays (McLemore, 2021; mindat.org, n.d.). The Lithium in these clay minerals is extracted by acidification and salt roasting, with some chlorination and alkalization methods also used (Zhao, et al., 2023). These processing methods involve some fairly complicated and potentially expensive chemistry Zhao and his co-authors discuss at length in their paper.

Lithium mining from clay deposits is happening in Mexico (Sonora Lithium Project), Serbia (Jadar Lithium-Borates Project), Australia (Bald Hill Lithium and Tantalum Mine, Figure 5), and in the United States (Kings Valley Lithium Exploration Project, Nevada) (Cadence Minerals, 2022; Mining Technology, 2021; Mining Technology, 2020; Lithium Nevada Corp., 2021).

Figure 5: Bald Hill Lithium and Tantalum Mine, Kambalda, Western Australia.

5.3. Brines, Evaporates and Geothermal Fluids

Today most Lithium production world-wide comes from brines and subsurface fluids which includes solar evaporates, playa lakes, and extracted fluids from petroleum and geothermal production (McLemore, 2021). This type of Lithium mining typically involves drilling into a subsurface fluid source, pumping the fluids to surface evaporation ponds, and then letting solar heat evaporate the water to concentrate the Lithium and other minerals. Subsequent processing refines the desired materials. This evaporation process is commonly used to mine multiple evaporate minerals such as Halite and Sylvite along with Lithium and others. Due to relatively low production costs, especially considering the other minerals that can be co-produced with Lithium, these types of deposits provide approximately three-fourths of the world's Lithium production (Munk, et al., 2016).

Munk and her co-authors delineate six common features shared by continental Lithium-rich brine production systems: 1) arid climate; 2) closed basin containing salar (salt crust), a salt lake, or both; 3) associated igneous and/or hydrothermal activity; 4) tectonically driven subsidence; 5) suitable Lithium sources; and 6) sufficient time to concentrate the Li-rich brine (Munk, et al., 2016).

Two large-scale brine deposits currently being processed for Lithium are the Salar de Atacama in Chile (the world's largest producing Lithium brine operation) and Clayton Valley in Nevada (longest production of Lithium brine) (Munk, et al., 2016).

Figure 6: Evaporation ponds at the Clayton Valley Lithium Mines as seen from Silver Peak, Nevada.

photo Ray Dunkin, 2017

5.4. Lithium Recycling

Another source of Lithium is recycling. Unfortunately Lithium recycling, especially from batteries, is very problematic. According to a study by the *Journal of the Indian Institute of Science*, just 1% of Lithium-ion batteries get recycled in the U.S. and EU compared to 99% of lead-acid batteries (Evergreen, 2022). Batteries are a multi-commodity item and processing them back to their constitute components is difficult and costly. *De-manufacturing* is a factory-based recycling system being developed by Telsa and other companies whereby materials are reprocessed and recycled as component materials in the production stream rather than just at the end recycling finished batteries (Evergreen, 2022).

For Lithium and other such industrial materials we need to build a circular economy—recycling considerations must be part of how batteries are designed, manufactured, distributed and recycled. American Battery Technology Corp CEO Ryan Melsert, who is involved with some of the "gigafactories" for Telsa, explains the circular battery economy: "Once these metals are mined once, you can essentially keep them in that loop indefinitely" (Evergreen, 2022).

Figure 7 illustrates one model for Lithium's life-cycle of production-manufacturing-use-recycle-reuse.

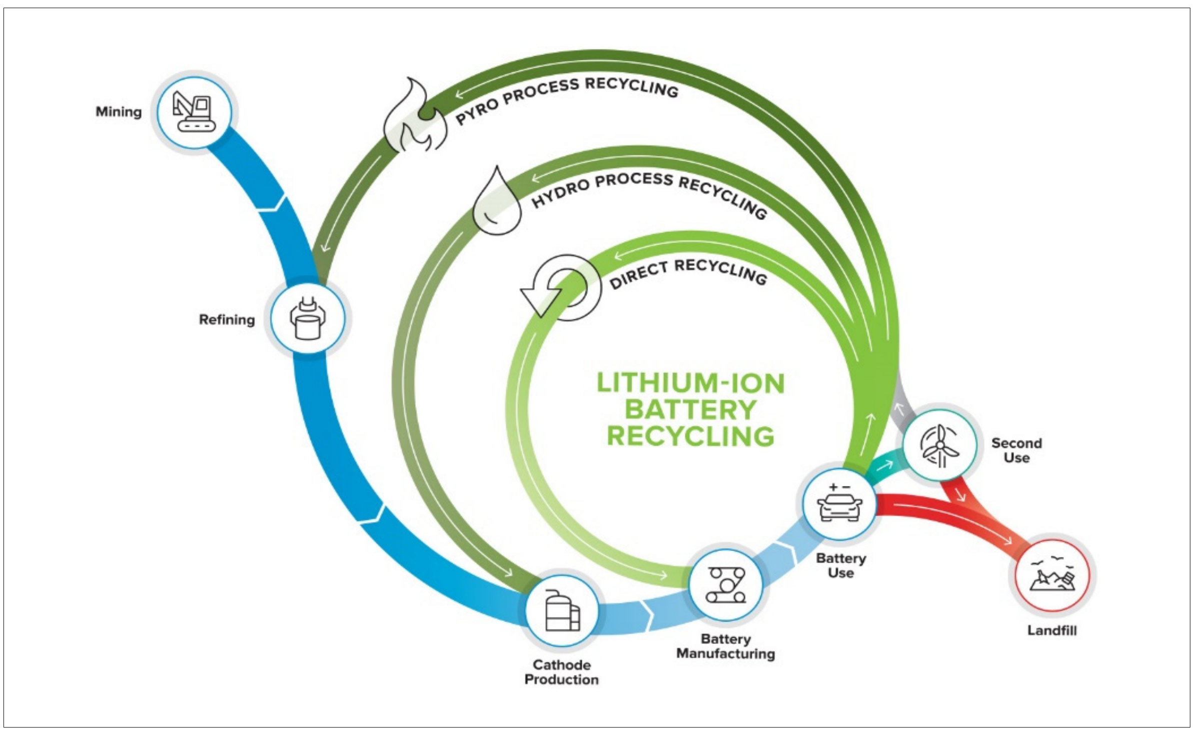

Figure 7: Life-cycle model for Lithium that includes recycling and reprocessing of materials at various stages of production and manufacturing (Evergreen, 2022).

6. Lithium in the United States

Lithium is found across the United States in varying concentrations. One measure of Lithium's American distribution are the amounts in our well-based public water systems. Figure 8 shows this distribution. Higher levels of water Lithium tend to be mostly in the southwest with very low concentrations in the central and southeast portions of the country (Branwen, n.d.).

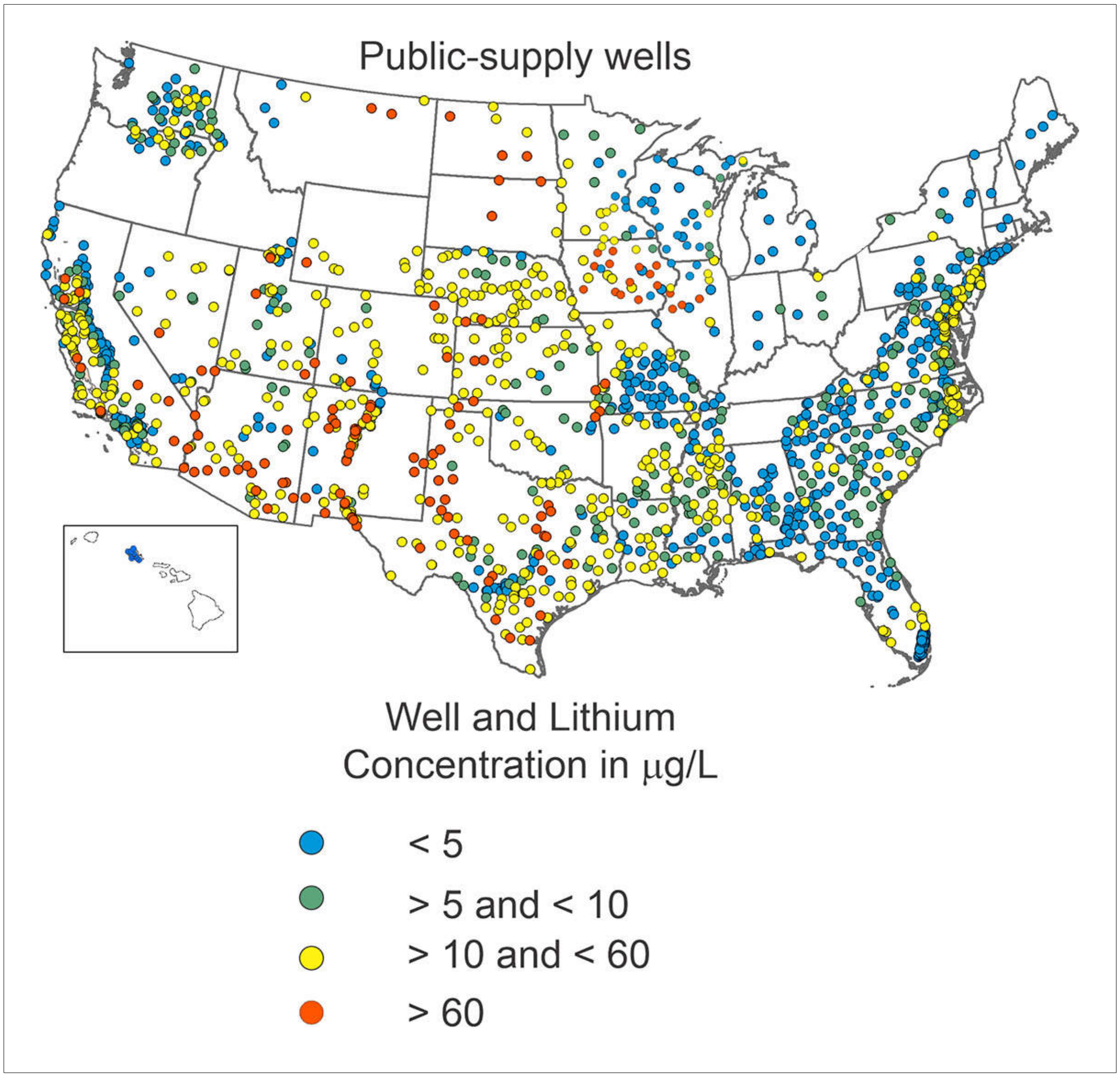

Figure 8: Concentrations of Lithium in well-based public water systems across the U.S. (Branwen, n.d.). Note higher values in the southwest and lower values in central and southeast parts of the country.

6.1. Lithium Mining and Battery Development Projects

Not necessarily reflecting the Lithium levels in our waters is the distribution of numerous Lithium mining and battery production projects currently underway across the country. In addition to the previously discussed Lithium mining at Kings Valley and Clayton Valley in Nevada, several other mining projects are currently under various stages of development shown in Figure 9.

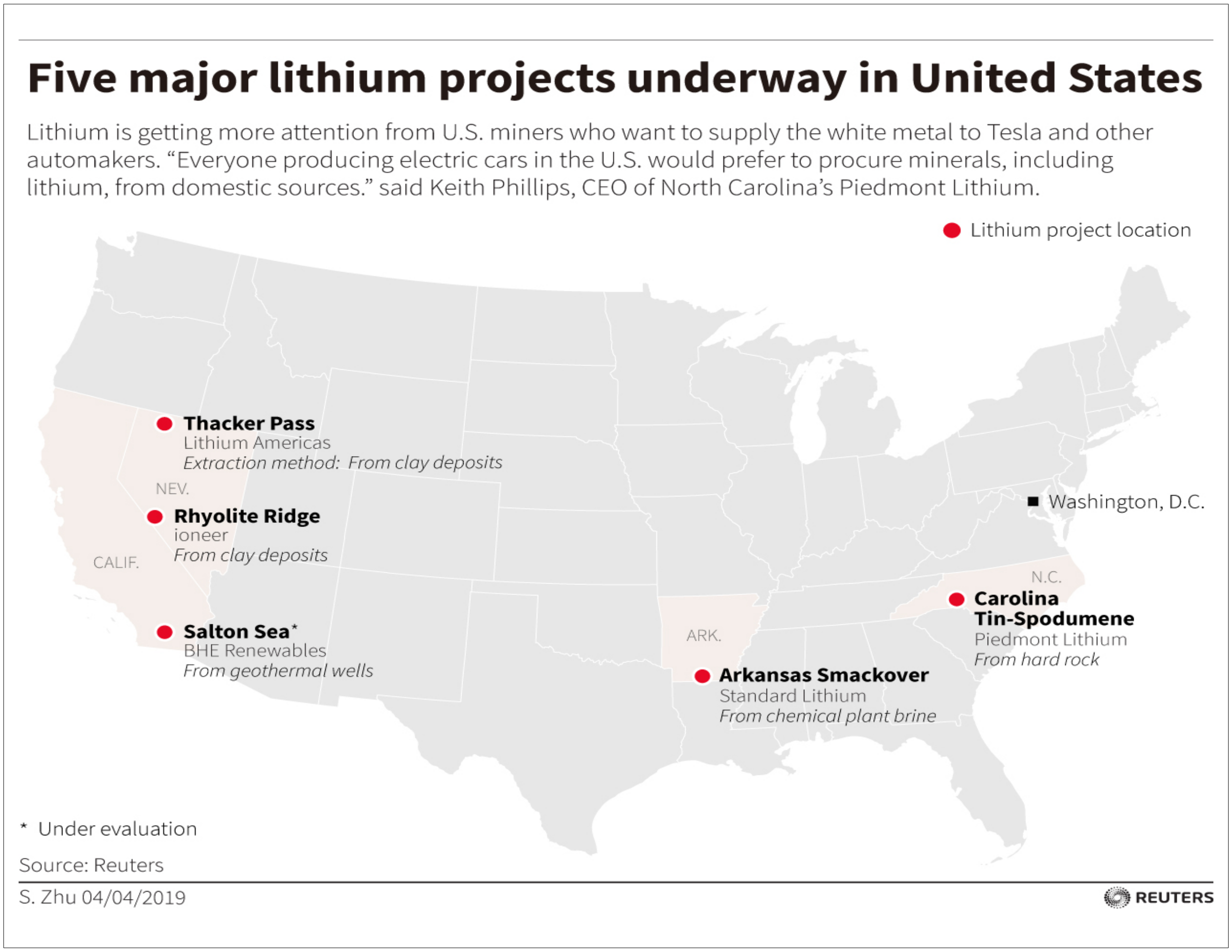

Figure 9: Lithium mining projects currently under development in the U.S. Thacker Pass and Rhyolite Ridge are clay deposits, the Salton Sea and Arkansas Smackover projects are subsurface fluid deposits, and the Carolina Tin-Spodumene location is a hard rock mine (https://piedmont-lithium.com/archived-/).

Even more so than the development of Lithium sources are the efforts being undertaken to build battery and battery component factories in the U.S. and Canada. Across the countries these so-called “gigafactories” are in various stages of planning, designing and construction by many companies as shown in Figure 10.

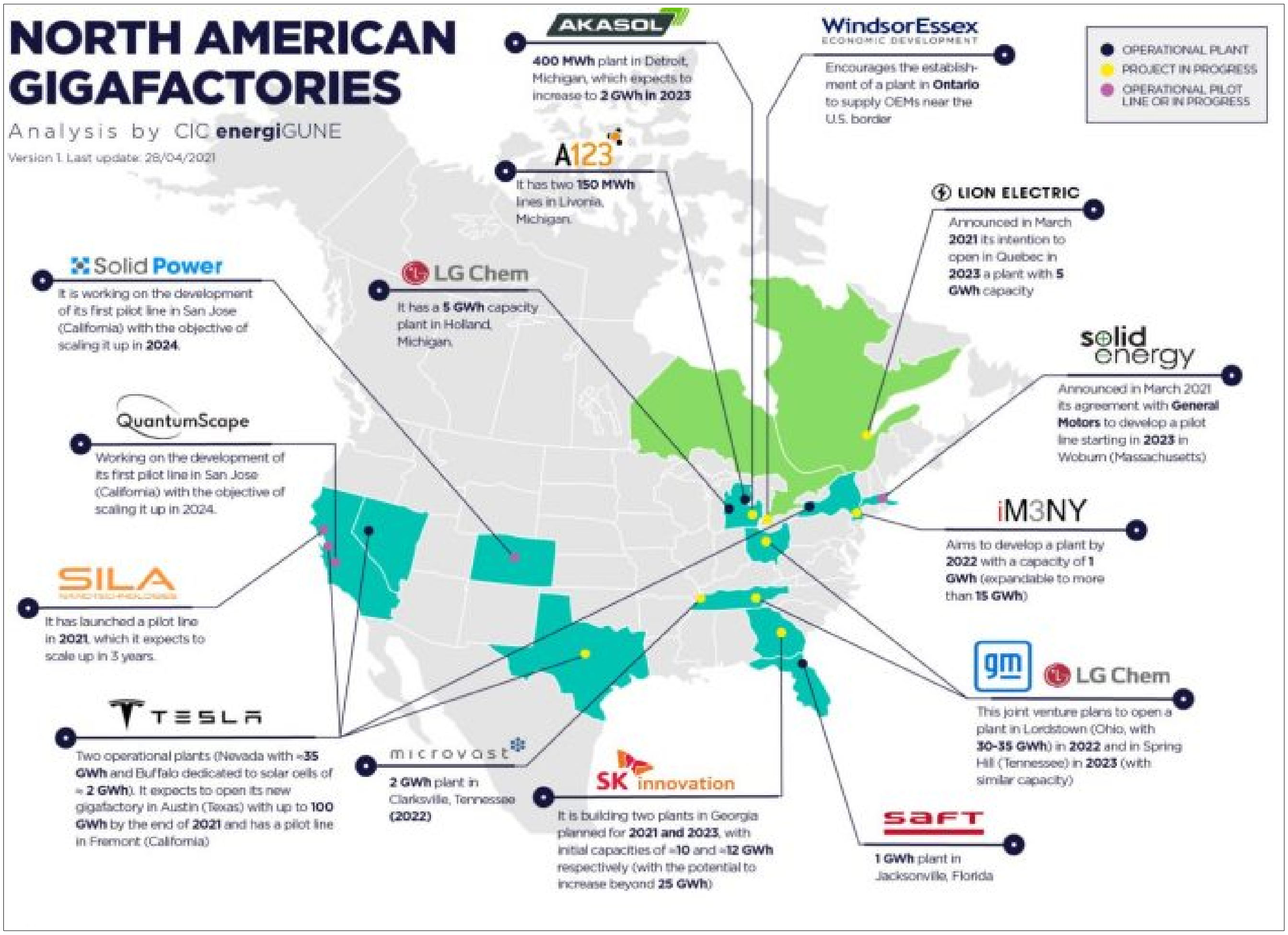

Figure 10: Battery 'gigafactories' in various stages of planning, design and construction across North America (CIC EnergiGune, 2022).

6.2. Known Deposits, Unknown Future Development

We have already discussed several Lithium mining projects and battery factory development efforts but two other Lithium resources are worth mentioning. On the west side of the country efforts are underway to co-produce Lithium and other minerals with geothermal energy at the Salton Sea in southeast California. On the other side of the country in Maine, legal battles are being fought over the development of a Lithium mine at the Plumbago North Pegmatite near Newry in the western part of the state (Figure 11).

Geothermal energy has been produced at the Salton Sea for many years with 11 power plants generating about 400 MW of electrical power. Now a pilot test plant is being built to produce Lithium and other minerals from the fluids extracted for geothermal energy production. Since the power plants already exist much of the needed infrastructure is currently in place (power, potable water, roads, etc.).

The plan is to continue pumping subsurface fluids for geothermal energy production. Instead of just pumping the cooler fluids back down into the ground, the plant will then pass the fluids over glass beads and a catalyst. Periodically the beads are flush with acid and lithium chloride remains. Additional processing will create lithium carbonate and/or lithium hydroxide that can be shipped to battery manufacturers (Brigham, 2022). Recall that Lithium metal is much too reactive to be handled and transported safely so producing carbonate or hydroxide make a much more stable and safer product. After mineral extraction, the geothermal fluids are pumped back into the ground as before.

This development project has received much press coverage over the past year. Just this past weekend CBS's *60 Minutes* featured a segment on mineral extraction efforts at the Salton Sea (CBS News, 2023).

Meanwhile, almost 3000 miles away in Newry Maine, efforts are being made to develop the Plumbago North Pegmatite for Lithium and other pegmatite minerals.

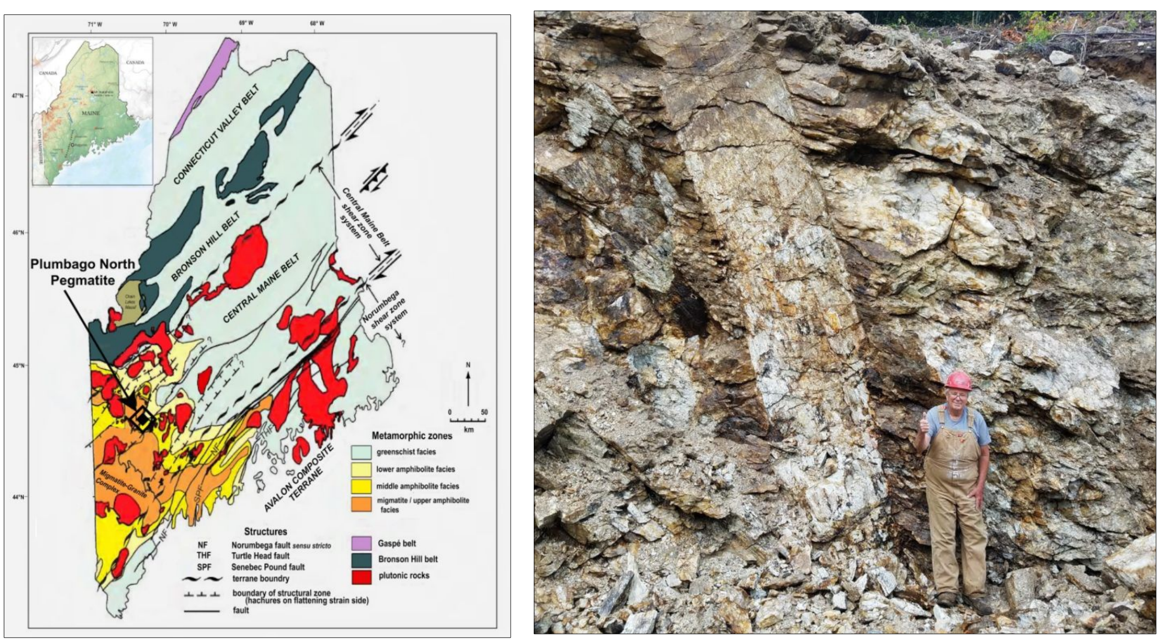

Figure 11. Geologic Map of Maine showing location of Plumbago North Pegmatite on the west side of the state (left) and an outcrop of the Plumbago Pegmatite with a large spodumene crystal typical of pegmatite mineral formations (right) (Cough, 2021).

“The Plumbage deposit’s potential is staggering. Current estimates are 11 million tons of ore valued at $1.5 billion” (Cough, 2021). Aside from its value as Lithium ore, Spodumene crystals over 35 feet long have been found, which rank among the largest ever found (Figure 11) (Simmons, et al., 2020).

Alas, not all is well at the mine. Recent changes to Maine’s mining laws, which severely limit the size of open pit metal mines, make it unclear if the deposit could be developed in the foreseeable future (Cough, 2021). Maine residents and legislators are very weary of changing the mining laws again because of previous mining endeavors that cost the state to clean up and remediate. Even if the laws were changed to allow the mine, other legal challenges are being brought by environmentalists and adjoining land owners. Suffice to say it will be many years, if ever, that the first batch of Lithium is shipped from Plumbago.

7. Lithium Prospects in New Mexico

Closer to home there are prospects for Lithium development in New Mexico. Although currently not in production in our state, we accounted for about 10% of U.S. Lithium output from 1920 to 1950. Most of that production came from the Harding Pegmatite Mine in the Picuris District, Taos County. Since 1950 no Lithium has been mined in here but work is currently underway exploring sources of Lithium in the state that could be economically produced. There are several known Lithium-rich pegmatites in north-central New Mexico but these are not likely to be developed in the near future. Volcanic clays occur across many parts of the state and a few have potential for development in the near-term. The Popotosa Formation of the Rio Grande Rift has notable amounts of Lithium in its tuff layers (up to 3800 ppm Lithium). Diatomite and zeolite deposits in the Gila Conglomerate in the Buckhorn area near Silver City offer another potential source of Lithium (14-200 ppm Li). Brine and hydrothermal/geothermal deposits offer some of the best sources of Lithium and other minerals in the short term. The Lordsburg, Tularosa, and Estancia basins all have measurable amounts of Lithium that make them potential development areas (124 – 624 ppm Li) (McLemore, 2021).

The New Mexico maps on the next page illustrate these Lithium potential areas and also show where NMBGMR and NM Tech research projects are underway exploring for Lithium, REEs, and other critical minerals.

- Porphyry deposits
- Carbonatites
- Mine wastes
- Coal, coal wastes and related materials (humates)
- Subsurface fluids

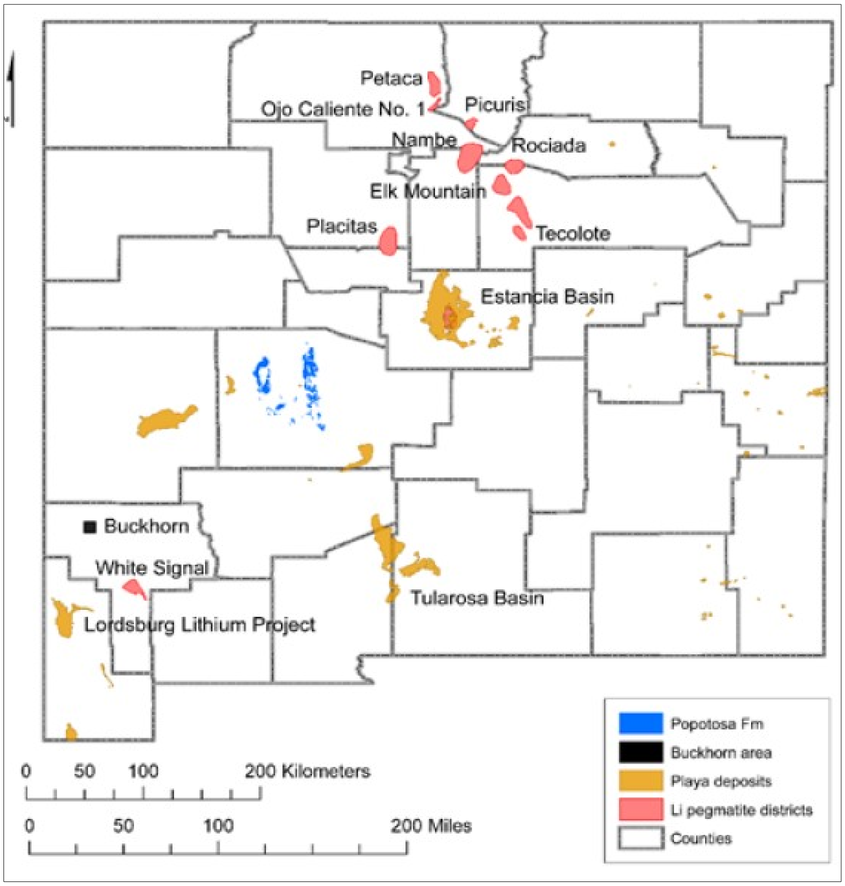

Figure 12: Areas in New Mexico that contain potential Lithium deposits (McLemore, 2021).

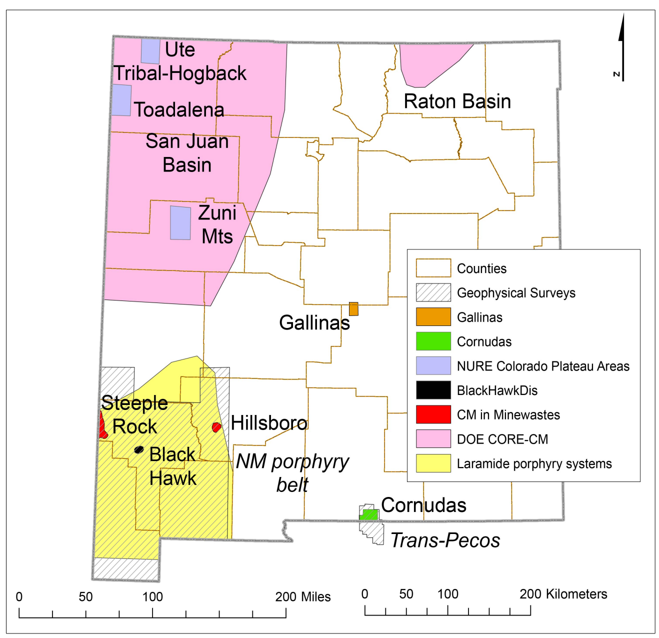

Figure 13: Areas in New Mexico currently being explored for Lithium and other critical minerals (McLemore, 2021).

8. Summary

Lithium is a critical industrial mineral vital to modern living. It is used in lubricants, medications, glass, ceramics, metal alloys, and most importantly, in batteries and power systems. In the past 10 years Lithium's use in batteries has increased from using one-quarter all produced Lithium to consuming three-quarters of the available material. To keep pace global Lithium production has increased from about 5000 tonnes annually in 1980 to over 105,000 tonnes in 2021—more than a 20-fold increase in 40 years!

The market price of Lithium reflects these changes. From mid 2017 through mid 2021 a tonne of Lithium traded on average for about US$15,000. For most of the last 2 years the price has been above US$70,000 per tonne. Early this year the value dropped to less than US$30,000 per tonne due to decreased demand in China and several new production areas coming on-line, notably in China, Australia and Chile.

Lithium is found in three types of deposits: pegmatites, volcanic clays, and from brines including subsurface fluids and evaporates. Pegmatites are currently mined in Australia, Czech Republic, Canada, and Zimbabwe. Volcanic clays are produced in Mexico, Serbia, Australia, and the United States. Globally, the most prolific production of Lithium comes from brines and subsurface fluids. Chile leads the way with the largest Lithium producing brine operation at Salar de Atacama. The U.S. has long produced Lithium and other evaporates at Clayton Valley in Nevada but nationally we rank 8th among producing countries.

Another source of Lithium is recycling but only 1% of Lithium batteries are actually recycled in the U.S. and EU. A great deal of work needs to be done in this area.

Lithium at varying levels occurs across the U.S. but not in economically viable deposits. A few locations in California, Nevada, Arkansas, North Carolina, and Maine are possible sources but with few exceptions most are many years away at the earliest from production. Co-producing Lithium with existing geothermal operation at the Salton Sea offers the shortest path to Lithium production.

New Mexico, once the producer of 10% of U.S. Lithium, has not shipped any since 1950. Many efforts are underway examining the potential for development from pegmatites, volcanic clays, and evaporate deposits around the state. We could again be a major player in the U.S. production of Lithium and other critical minerals. Much work, in the geosciences, social sciences, and legal fields, must be done to promote the growth of industrial minerals in the Land of Enchantment.

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