LITHIUM IN NEVADA

Origins, Extent, Role in the Energy Transition, and Implications for Economic Development and National Security

Nevada Bureau of Mines and Geology Special Publication 40

Nevada Bureau of Mines and Geology

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Origins, Extent, Role in the Energy Transition, and Implications for Economic Development and National Security

Simon M. Jowitt[1], Christopher D. Henry[2], Jorge Crespo Mena[2], Cary R. Lindsey[2], Michael H. Darin[3], Daniel M. Saftner[4], Kevin M. Heintz[4], and Ronald L. Hershey[4]

[1]Ralph J. Roberts Center for Research in Economic Geology, Nevada Bureau of Mines and Geology, University of Nevada Reno, Reno, NV, USA (sjowitt@unr.edu)
[2]Nevada Bureau of Mines and Geology, University of Nevada, Reno, Reno, NV, USA.
[3]Oregon Department of Geology and Mineral Industries (DOGAMI), Portland, OR, USA
[4]Desert Research Institute, Reno, Nevada, USA.

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Executive Summary

Lithium is critical to the ongoing transition from fossil fuels to low- and zero-carbon-dioxide (CO_2) energy produced from renewable resources. The current dependence of the U.S. on foreign sources of lithium and on the batteries needed to power electric and hybrid vehicles, grid-scale electric storage for solar and wind renewable energy, computers, cell phones, and many other high-tech devices is a national security and economic concern. Domestic supplies of the raw materials required to support expanding domestic manufacturing and recycling in this area and others are therefore needed.

Nevada is a lithium hub, with active mining, numerous lithium deposits, lithium processing, battery manufacturing, recycling, and research in numerous areas. Lithium has been extracted at the Silver Peak brine operation in Clayton Valley (Esmeralda County) since 1966, and Nevada leads the nation in lithium production. Several lithium-clay deposits in Nevada are likely to be mined in the next few years and decades, and many more clay and brine deposits have been discovered but are not currently economically viable. Research at Nevada System of Higher Education institutions is underpinning advances in understanding the formation of lithium deposits, optimizing the processing of lithium ores, and protecting the biodiversity and environment around potential operations.

In addition to the natural resources required for the energy transition, Nevada is well positioned to provide the clean, renewable energy that forms a crucial part of this transition. Clear skies most days in the Silver State make solar power ideal. Geothermal resources are also abundant in Nevada, with many power plants providing local power to the electric grid. Hydroelectric and wind power generation are also significant for our state, and the reliability of all of this renewable energy is increasingly supported by grid-scale battery storage, indicating another potential use for the lithium extracted in Nevada.

Introduction

Nevada, renowned for its expansive desert landscapes and rugged terrain, boasts not only breathtaking natural beauty but also a wealth of geological resources. The Silver State is also unique in the lithium world in that Nevada contains not just sources of lithium in the form of natural mineral deposits that can be used to supply lithium to industry but also all other aspects of lithium-ion battery manufacturing and recycling (figure 1). The lithium-ion battery manufacturing present in the state, such as at the Tesla/Panasonic Gigafactory in Sparks, requires large amounts of lithium to operate. The natural geological processes that occurred over the past tens of millions of years in Nevada have generated a number of different types of lithium resources. However, as is the case for the development of all deposits outlined in this report, realizing the potential of these resources will require careful planning, technological innovation, and collaboration among stakeholders to balance economic, environmental, and social considerations. This report provides information on the processes involved in the formation of these resources, the size and nature of the lithium endowment in the state, and the important role that Nevada will play in providing lithium to industry in Nevada and across the U.S.

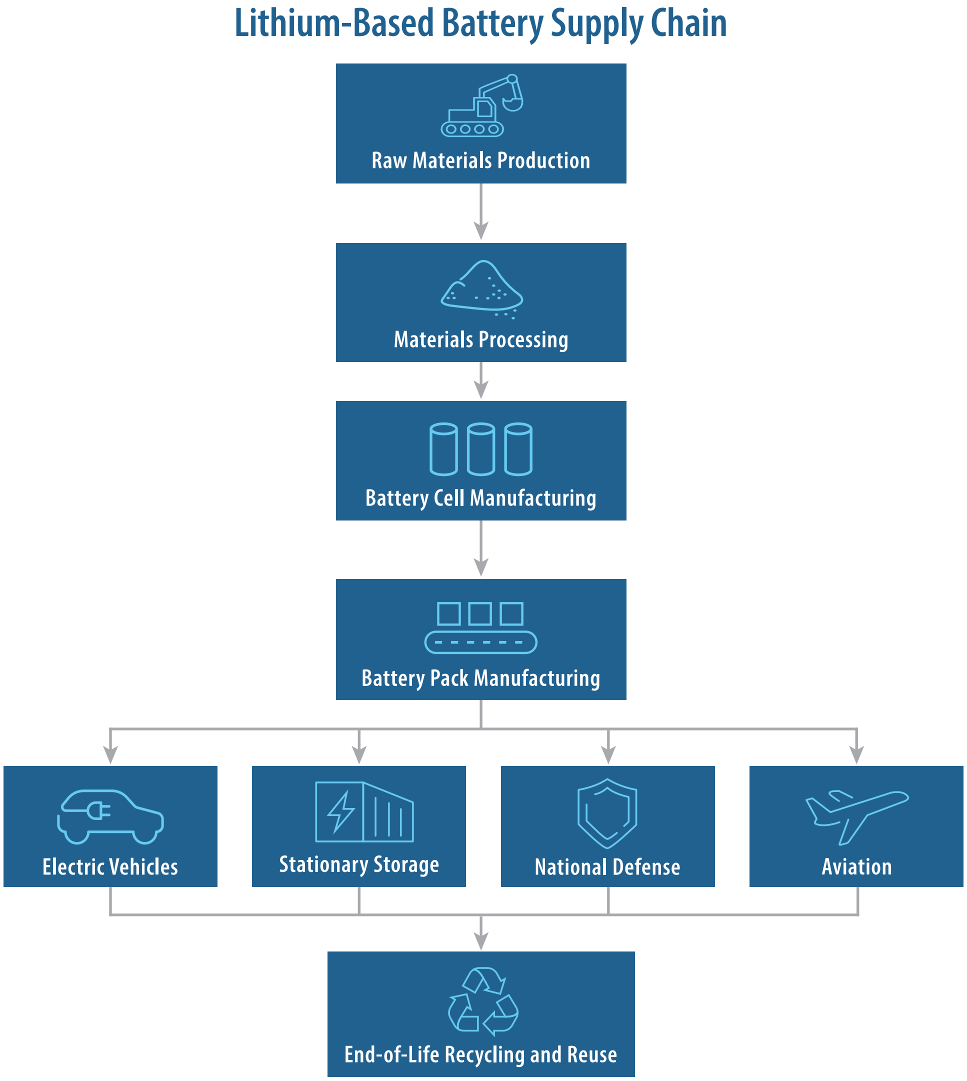

Figure 1. The lithium value and manufacturing chain, going from the extraction or mining of lithium through battery manufacturing, end-uses, and eventual recycling to establish a circular lithium economy.

3
Li
Lithium
6.941

What is Lithium?

Lithium is a silvery-white to gray alkali metal denoted by the symbol Li with atomic number 3. It is the lightest and least dense of all metals (figure 2). Lithium also has high electrical conductivity and low resistivity, properties that make it ideal for use in batteries, where it enables lighter and longer-life battery compositions.

Figure 2. 99.9% pure lithium showing the characteristic untarnished nature of this metal. Lithium metal rod in photo not to scale, diameter ~0.5 inch. (Björn Wylezich/stock.adobe.com)

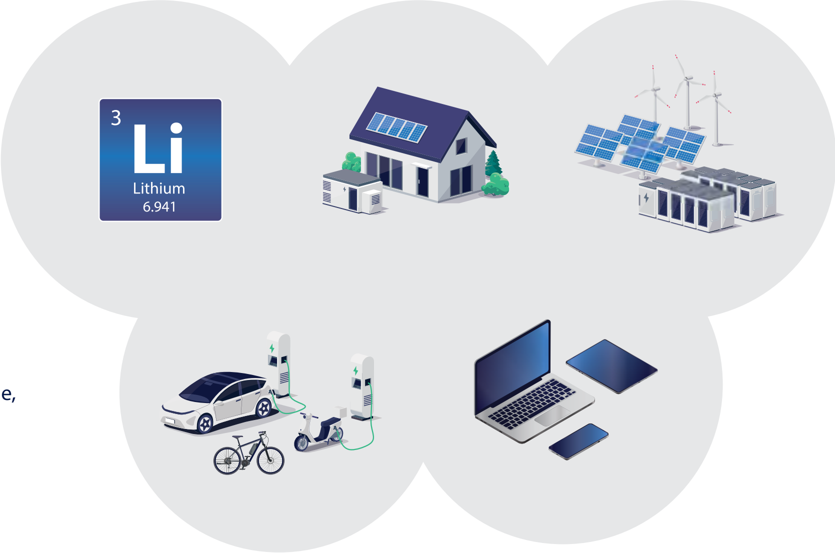

Figure 3. Uses of lithium-ion batteries, including in home and grid-scale storage, electric vehicles and bikes, and in smartphones and laptop computing.

Lithium is one of the commodities considered most crucial for the energy transition and the move to green energy generation, storage, and transport. It is also critical for a significant amount of battery manufacturing[1,2], principally of the lithium-ion batteries commonly used in electric vehicles but also with uses in home energy storage, grid-scale storage of energy generated by renewable energy sources such as solar or wind, and consumer electronics (cell phones and laptops; figure 1 and figure 3). Lithium also has a range of other uses, including ceramic and glass manufacturing, in lubricating greases, and in medication, although most current and future lithium use will be in the manufacturing of lithium-ion batteries. For example, the U.S. Geological Survey estimates that 87% of current lithium demand is from the battery sector[3], and this is likely to rise to 95% by 2030. This has led to the planning, development, and construction of many lithium-ion battery manufacturing facilities in the U.S., as demonstrated by the Tesla-Panasonic Gigafactory near Sparks, Nevada (figure 4) and by the map of existing or potential battery manufacturing facilities shown later in this report.

This increase in demand for lithium-ion batteries has led to a large increase in demand for lithium produced by conventional mining or from brines[4], as highlighted by the increases in lithium primary production shown in figure 5.

Figure 4. The Tesla-Panasonic Gigafactory, a lithium-ion battery manufacturing facility located near Sparks, Nevada. Photograph courtesy of Tesla.

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[1] https://pubs.geoscienceworld.org/segweb/segdiscovery/article/doi/10.5382/2021-127.fea-01/608409/Battery-and-Energy-Metals-Future-Drivers-of-the

[2] https://www.iea.org/reports/critical-minerals-market-review-2023/key-market-trends

[3] https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-lithium.pdf

[4] https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

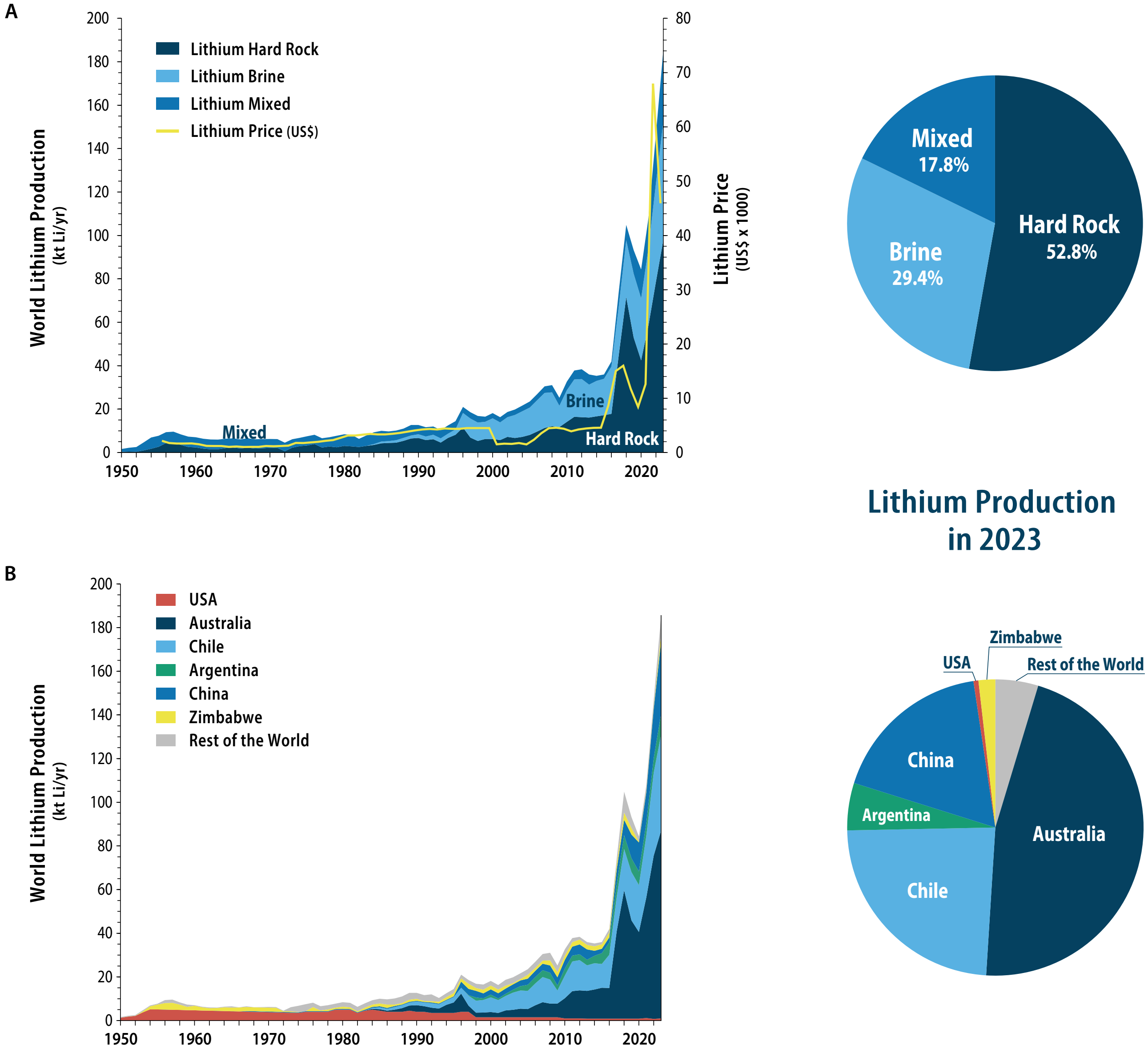

Figure 5. Global lithium production (in thousands of metric tons of contained lithium metal) from 1950 to 2023 expressed in terms of source type (A) and country of origin (B). The country of origin data indicates the dominance of Australian production in 2023 (86,000 tons of lithium metal) compared to other countries such as Chile (44,000 tons of lithium), China (33,000 tons of lithium), and the USA (1,000 tons of lithium), with total 2023 production of around 185,700 tons of lithium. Lithium price variations are also shown in A (uncorrected for inflation). Updated from [5,6].

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[5] https://www.lyellcollection.org/doi/full/10.1144/geoenergy2023-045

[6] https://www.mdpi.com/2071-1050/13/19/10855

The Lithium Cycle

All chemical elements, including lithium, cycle through the Earth's atmosphere, oceans and waterbodies, and rocks as a result of natural processes and increasingly human influence. All rocks, soils, and the atmosphere contain lithium, but generally at very low concentrations. The transfer of lithium from one part of this cycle to another involves a range of processes, including the following (figure 6):

- Rocks containing lithium break down by weathering and erosion, transferring lithium to rivers, lakes, or secondary minerals.
- Lithium in runoff travels through rivers and streams to lakes or the ocean, where it can precipitate as sediments.
- Deep-sea hydrothermal vents discharge lithium-bearing fluids derived from rocks beneath the seafloor to the oceans.
- Magmas that move through the Earth transfer lithium internally or erupt as volcanoes that discharge lithium-bearing gases and particles into the atmosphere.
- Volcanic emissions, sea-salt aerosols, and dust in arid environments move lithium through the atmosphere.
- Lithium can be removed from the atmosphere and added to water or land by the settling of airborne particles or by the dissolution of lithium into rain and other forms of precipitation.

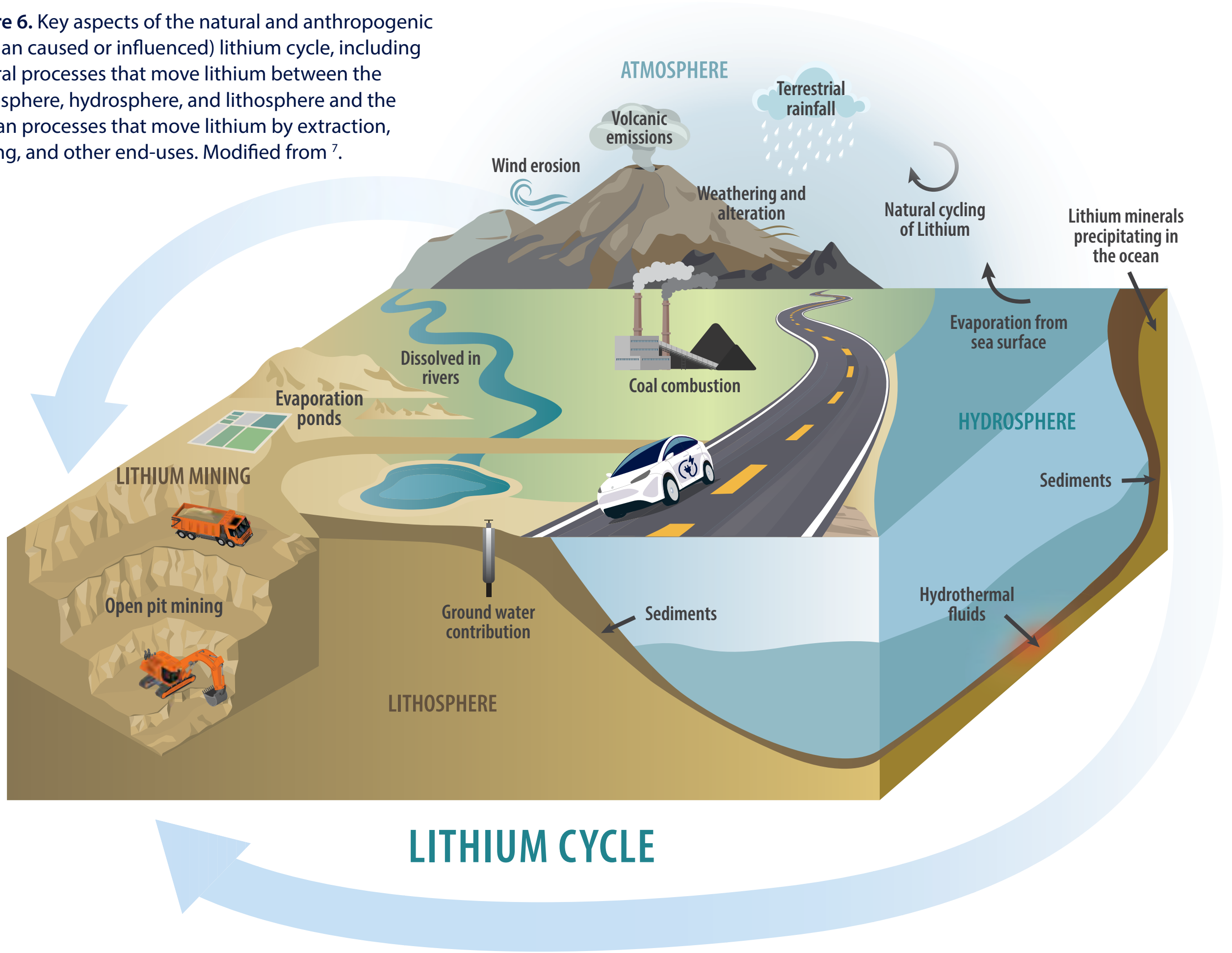

Figure 6. Key aspects of the natural and anthropogenic (human caused or influenced) lithium cycle, including natural processes that move lithium between the atmosphere, hydrosphere, and lithosphere and the human processes that move lithium by extraction, mining, and other end-uses. Modified from [7].

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[7] https://www.nature.com/articles/s41545-023-00238-w

A significant amount of lithium on Earth is present in minerals in the mantle and crust, which when dissolved can add lithium to rivers, lakes, groundwater, or seawater by basic hydrological circulation. This can result from the hot, hydrothermal fluids that are vented in the deep sea—and the waters that emanate in natural hot springs on the Earth's surface. The dissolved lithium can precipitate as new minerals within a different environment. The melting of minerals within the mantle and crust to form magmas can also incorporate lithium, which is then transported to form igneous rocks within other parts of the Earth, such as slow cooling granites within the Earth's crust or volcanic ash formed by explosive eruptions.

In very rare cases, these natural processes act to sufficiently concentrate lithium in forms where it can be extracted through hard-rock mining or other techniques, providing a supply of lithium for modern society's needs. A rare convergence of many different geological processes is required for the formation of most commercially viable mineral or metal deposits (for example, copper, gold, zinc, and others). Such deposits are unusual, take a long time to form relative to human time spans, and are difficult to find. Therefore, the identification of economic deposits of any metal is challenging. All mineral and metal deposits require the following:

1. A **source** of metal, such as lithium. For Nevada deposits, this is typically a lithium-enriched magma or igneous rock. This source generally contains lower concentrations of lithium by tens to thousands of times compared to the concentration in the eventual deposit.
2. A way to **transport** the metal from source to deposit. For Nevada lithium deposits, this is often thought to be groundwater, especially a highly saline form called brine. The brine itself can be a lithium deposit or can contribute to formation of solid deposits, which, in Nevada, are lithium-bearing clays or sediments.
3. A **trapping process** and environment where the transported lithium can be trapped and concentrated to a sufficient level and in an extractable form to generate a potentially economic mineral deposit.

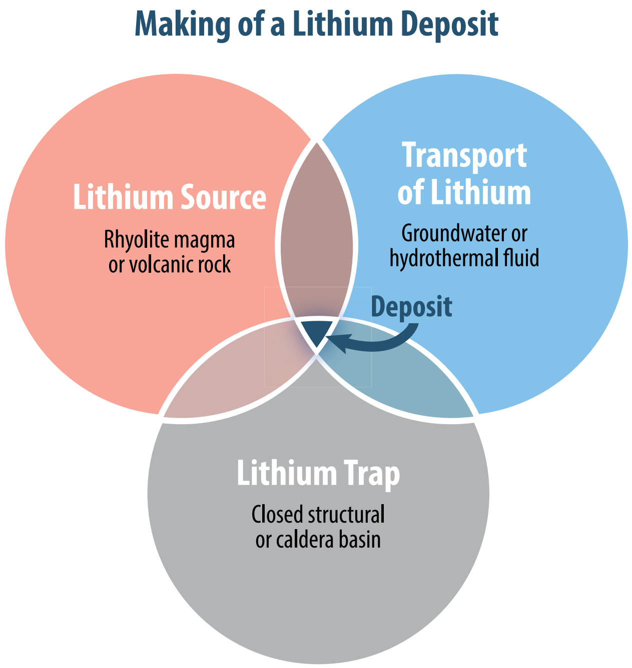

Figure 7. Key aspects of the formation of a lithium deposit. All mineral deposits, including all lithium deposits, need a source of a metal, a trap, and some way of transporting the metal.

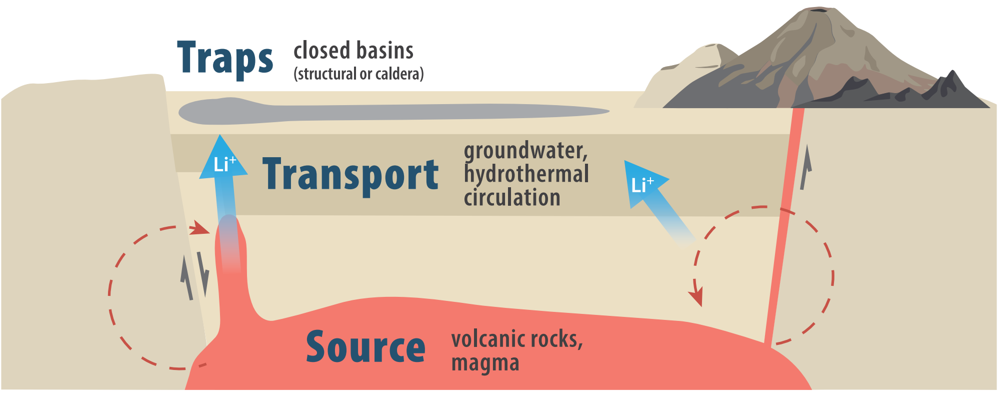

Figure 8. Geological model showing the key processes involved in the formation of a closed-basin lithium deposit.

Good examples of areas in Nevada containing all of these factors are closed sedimentary basins (figure 9), where surface water and groundwater flow in, but water can only leave by evaporation, acting to transport and concentrate lithium. Nevada's arid climate encourages evaporation. In addition, almost all of Nevada is in the Great Basin (figure 10), an unusual part of the U.S, where rivers flow into and are trapped within enclosed lakes and basins rather than reaching the Atlantic or Pacific Oceans. These areas are called "closed hydrologic basins" and represent potential or known targets for lithium exploration.

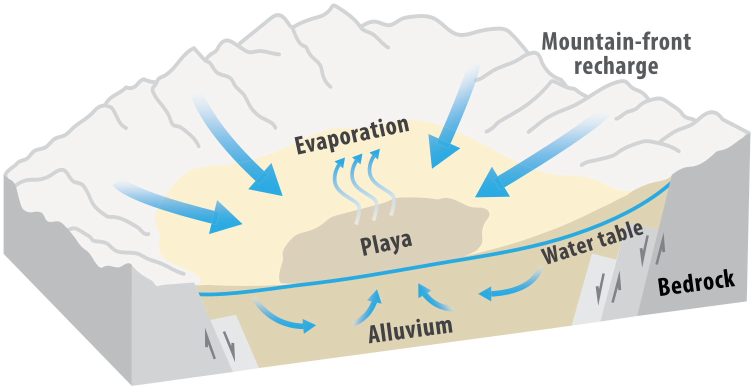

Figure 9. Model of a closed sedimentary basin, where surface and ground water flowing into an area can only leave by evaporation.

Human activities create an anthropogenic lithium cycle that rivals the overall natural cycling of lithium in the amount of total lithium moved from one part of the Earth system to another, including the processes that form mineral deposits. For example, the formation and movement of coal ash by the burning of coal, wastewater from oil and gas extraction, and the disposal of consumer electronics and other materials containing lithium-ion batteries all form part of an anthropogenic cycle of lithium that can move significant amounts of lithium between the lithosphere, hydrosphere, and atmosphere. This includes the extraction of lithium by conventional mining or other extractive techniques and the use of this lithium in the manufacturing of lithium-ion batteries, especially considering that lithium mined in Australia is currently generally used for battery manufacturing in China. This anthropogenic movement of lithium is thought to be far larger than natural lithium transport, perhaps by up to 500%[8].

Figure 10. Extent of the Great Basin of the western U.S.. All of the water flowing into this region can only eventually escape naturally by evaporation.

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[8] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021GB006999

Where do we find lithium?

Geological processes combine to deposit lithium in concentrations sufficient to allow economic development, as long as the lithium is present in an extractable form. The three primary processes and resulting groups of deposits that contain potentially economic amounts of lithium are:

1. **Salar or continental brine deposits**, formed from the concentration of lithium in evaporative brines (extremely salty groundwater containing a variety of metals in solution). The lithium brine at Silver Peak in Clayton Valley, Nevada is at the time of writing the only primary lithium producer in the U.S. (table 1).

2. **Hard-rock deposits**, predominantly lithium-rich pegmatites, which are derived from nearby bodies of magma and are generally granitic in composition (high in silica). No major hard rock lithium deposits have been identified in Nevada.

3. **Clay- or sediment-hosted deposits**, which are commonly solidified sediments infused by or representing the residue of lithium brines. Such deposits are the main type of lithium resource in Nevada but are currently an unproven resource because no clay- or sediment-hosted clay deposit is currently mined economically (table 1). Many sedimentary or clay deposits have been identified within Nevada to date (table 1) and two deposits, at Thacker Pass and Rhyolite Ridge, are nearing but not yet producing.

4. **Oilfield brines, geothermal fluids, and lithium salts** have also been the focus of recent research but have no industrial-scale production of lithium to date. The potential for lithium extraction from geothermal systems in Nevada is discussed later in this report.

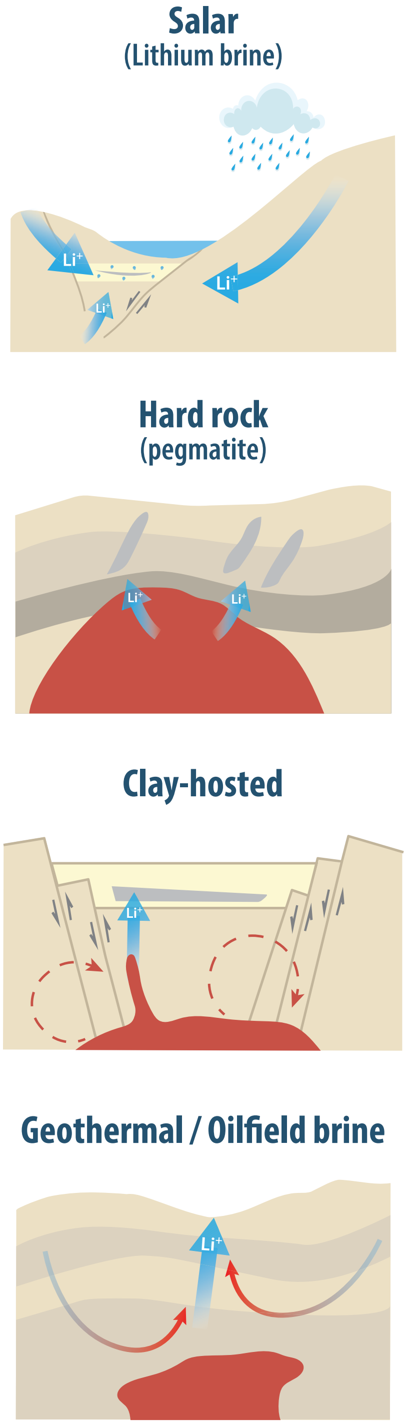
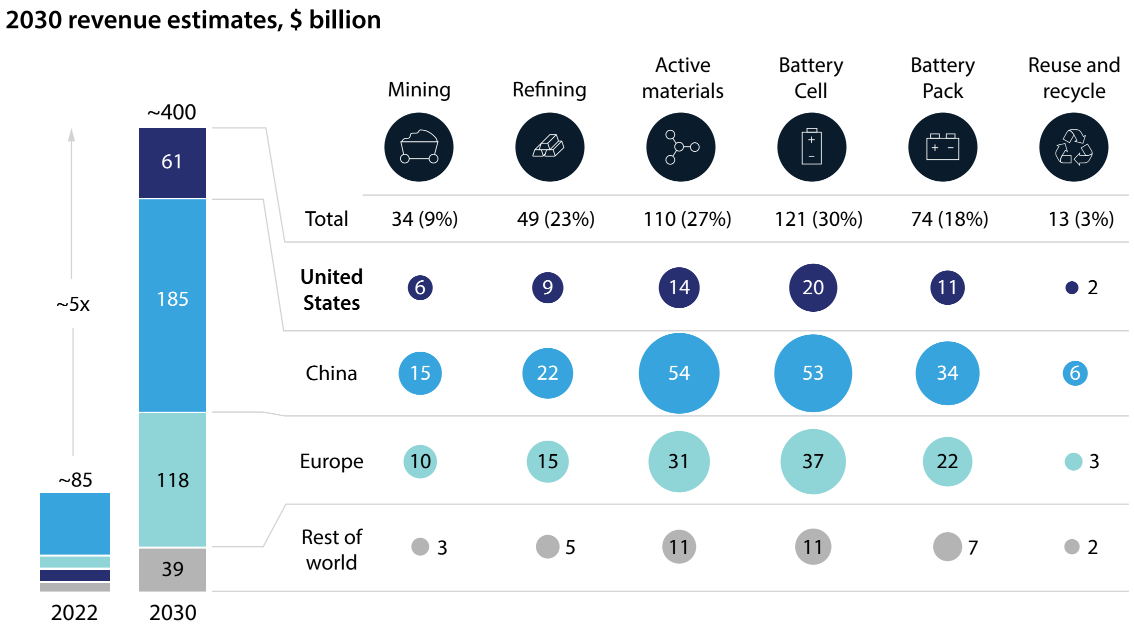


Figure 11. Different types of lithium mineral and brine deposits.

The Lithium Economy

The increase in battery manufacturing described earlier means that the value of the lithium-ion battery economy is also set to significantly increase, from ~$85 billion in 2022 to over $400 billion in 2030[8]. This value is split between mining, processing, battery manufacturing, and recycling (figure 12). However, without a secure supply of lithium to start this supply chain, increasing domestic and global battery manufacturing may not be possible with an associated loss in employment and economic development opportunities. Nevada is currently ideally suited to become a national leader in lithium production and lithium-ion battery manufacturing. Nevada is the only U.S. state that encompasses every facet of the lithium-ion battery economy and life cycle, from production by mining through to recycling[10]. The lithium sector in 2022 in Nevada already employed some 8,282–9,116 workers[11], with the current expansion of all aspects of the sector likely inducing significant future increases in both direct and indirect employment prospects.

However, these developments in the lithium sector will require significant amounts of raw materials, primarily from mining, given that recycling rates for lithium-ion batteries remain low. In addition, the amount of these metals in the current economy means that even a 100% recycling rate of the current relatively low amount of material in use could not meet increasing demand for the lithium needed for battery manufacturing and other uses[12].



Source: Adapted from McKinsey Battery Insights, 2022

Figure 12. Projected lithium value chain in 2030[13]. Note that the proportion of value increases significantly downstream from 9% value ascribed to mining to 27% for active material manufacturing and 30% for cell manufacturing. In addition, increased development of the lithium sector within the U.S. may mean that additional value moves toward the domestic lithium value chain rather than realized overseas.

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[9] https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular

[10] https://cber.unlv.edu/research-reports/the-lithium-ion-economy-may-2022/

[11] https://cber.unlv.edu/research-reports/the-lithium-ion-economy-may-2022/

[12] https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

[13] https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular

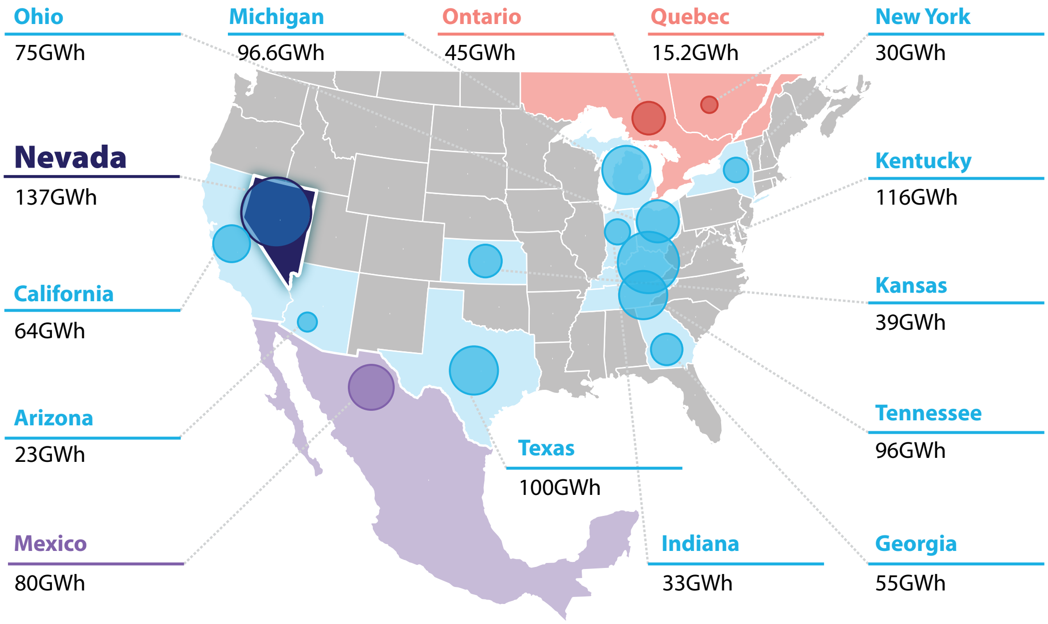

Figure 13. Total battery manufacturing capacity commissioned, under construction, and announced since the passage of the 2022 Inflation Reduction Act .

We can examine what amount of lithium is required to sustain a growing lithium-ion battery sector by considering typical lithium-ion battery manufacturing. This requires between 0.111 and 0.139 kg of lithium to produce 1 kilowatt-hour (KWh, or the equivalent of the energy delivered by one kilowatt of power for one hour of time) battery capacity[14]. For comparison a typical house in the U.S. uses around 900 KWh of electricity a month[15]. This lithium demand combined with the expansion of Nevada's lithium-ion battery manufacturing facilities will lead to an annual demand of approximately 15,200 metric tons of lithium for the state alone. Current total primary U.S. production, or the total amount of lithium we extract from the ground in the U.S. is still predominantly from the Silver Peak lithium brine operation in Nevada. This production in 2024 is approximately 5,000 metric tons lithium carbonate equivalent or 1,000 metric tons lithium metal equivalent[16]. Global production in 2024 was around 180,000 metric tons of lithium metal equivalent. Comparing this demand and supply indicates that the planned battery manufacturing capacity of the state of Nevada will consume 15 times current U.S. production of lithium. Importantly, the planned battery manufacturing capacity of the U.S. as a whole (figure 13) will likely grow so that approximately 412,000 metric tons of lithium carbonate equivalent (77,373 metric tons lithium metal equivalent) will be needed by 2030[17], indicating the rapid expansion of the U.S. (and Nevada) lithium-ion battery sector and the need to find the lithium resources to support this expansion.

Approximately 20% of lithium extraction currently occurs in China, and much more lithium mining and extraction globally is partially or entirely controlled by Chinese companies. This, coupled with 50% of global lithium refining capacity currently located in China raises important economic and security concerns, putting the U.S. in a vulnerable position. Steps are needed to ensure security of lithium supply for U.S. battery manufacturing facilities as well as to hedge against potential supply chain disruption by global or regional events.

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[14] https://www.sciencedirect.com/science/article/abs/pii/B9780443185151000150

[15] https://www.eia.gov/energyexplained/use-of-energy/electricity-use-in-homes.php

[16] Lithium resources and reserves are often reported as lithium carbonate or lithium hydroxide equivalents rather than lithium metal, so 1 metric ton of lithium metal is approximately 5.323 metric tons of lithium carbonate equivalent or 6.06 tons of lithium hydroxide equivalent.

[17] https://www.fastmarkets.com/insights/us-lithium-demand-to-grow-fastmarkets-provide-regional-price-transparency/

Lithium in Nevada

Nevada currently has the largest known resources and reserves of lithium in the U.S., as outlined in table 1. This means Nevada is ideally suited to be the main supplier of lithium to the U.S. lithium-ion battery sector. It is important to understand how these lithium mineral deposits form and where they are located, key processes that are being actively investigated by researchers at the Center for Research in Economic Geology at the Nevada Bureau of Mines and Geology. This section focuses on the different types of lithium resources in Nevada, outlining how they formed and the key geological processes that concentrated lithium in these systems.

Table 1. Current resources and reserves of lithium in Nevada; the geographical distribution of these deposits is shown in figure 14. Although the totals are quite large, many of the listed resources are unlikely to become economic in the next decade, given the 1) current price of lithium, 2) the volatility of lithium pricing, 3) the required technologies for extracting lithium from clay deposits and brines, 4) the concentrations of lithium in the deposits, and 5) the time needed to obtain the requisite permits and permissions to develop a lithium extraction operation.

Deposit	Company	Type of Deposit	Reserves (Mt contained LCE)	Resources (Mt contained LCE)	Current/Proposed Annual Production (kt/yr LCE)	EV equivalent	Source and Notes
Thacker Pass	Lithium Americas	Clay/sedimentary	3.7	19.1	Phase 1 40 Phase 2 80	449 million	https://lithiumamericas.com/files/doc_financials/2023/ar/NewLAC-ThackerPassFeasibilityStudyNI43-101-October2023.pdf
Clayton Valley	Century Lithium	Clay/sedimentary	1.76	6.67	~26	157 million	https://www.centurylithium.com/_resources/technical-reports/252456-0000-BA00-RPT-0003_ClaytonValley_NI%2043-101_12June2024.pdf?v=070205
Rhyolite Ridge (also contains boron)	Ioneer	Clay/sedimentary	0.58	3.35	Stage 1, ~22.3 Stage 2, ~19.3	79 million	https://wcsecure.weblink.com.au/pdf/INR/02657829.pdf, https://www.ioneer.com/wp-content/uploads/2022/07/300420-dfs-executive-summary-metric_final.pdf
Silver Peak	Albemarle	Brine	0.36	1.00	Currently ~5, proposed doubling to ~10	26 million	https://s201.q4cdn.com/960975307/files/doc_financials/2023/q4/9aefa2f5-78dc-4015-bf20-b71aba0bb593.pdf
Tonopah Flats	American Battery Technology	Clay/sedimentary		18.6		436 million	https://americanbatterytechnology.com/wp-content/uploads/ABTC-TonopahFlats-MII-Resource-Update-IA-Report-Apr-2024.pdf
Bonnie Claire	Nevada Lithium	Clay/sedimentary		18.4		431 million	https://nevadalithium.com/wp-content/uploads/2023/08/Bonnie-Claire_PEA-Technical-Report_02-25-2022.pdf
TLC	American Lithium	Clay/sedimentary		10.7		251 million	https://americanlithiumcorp.com/wp-content/uploads/2023/05/PEA-Report-TLC.pdf
Horizon Lithium	Pan American Energy Corp	Clay/sedimentary		10.2		240 million	https://panam-energy.com/wp-content/uploads/2024/01/NI-43-101-TR-Pan-American_Horizon-Lithium_January_2024.pdf
Gemini	Nevada Sunrise	Clay/sedimentary		7.1		167 million	https://nevadasunrise.ca/site/assets/files/4151/nevada_sunrise_metals_corp_ni_43_101_technical_report_r.pdf
Zeus	Noram Lithium	Clay/sedimentary		6.3		147 million	https://noramlithiumcorp.com/site/assets/files/3997/2023-03-20-updated-resource-estimate-zeus.pdf
Lone Mountain	Future Battery Minerals	Clay/sedimentary		6.2		146 million	https://www.investi.com.au/api/announcements/fbm/2cf7cdbb-7b0.pdf

Deposit	Company	Type of Deposit	Reserves (Mt contained LCE)	Resources (Mt contained LCE)	Current/Proposed Annual Production (kt/yr LCE)	EV equivalent	Source and Notes
Nevada North	Surge Battery Metals	Clay/sedimentary		4.7		110 million	https://wp-surgebatterymetals-2024.s3.ca-central-1.amazonaws.com/media/2024/04/Surge-NNLP-NI-43-101-Report-04-05-2024.pdf
Clayton Ridge	Amani Gold	Clay/sedimentary		2.6		60 million	https://authium.com.au/project/, https://www.amanigold.com/wp-content/uploads/2023/12/AGREEMENT-TO-ACQUIRE-MAJOR-LITHIUM-RESOURCE-IN-NEVADA.pdf
McGee	Spearmint Resources	Clay/sedimentary		2.1		49 million	https://www.spearmintresources.ca/wp-content/uploads/2022/06/MLC-Deposit-NI-43-101-Final-TR_6-17-2022.pdf
West Tonopah	Enertopia	Clay/sedimentary		0.66		15 million	https://enertopia.com/wp-content/uploads/2023/11/Enertopia-NI-43-101-MRE-Techical-Report-Nov2023.pdf
Clayton	Acme Lithium	Brine		0.30		7 million	https://acmelithium.com/wp-content/uploads/2024/03/ACME-Lithium-Clayton-Valley-43-101-3.13.2023-FINAL-.pdf
Clayton Valley South	Pure Energy Minerals	Brine		0.22		5 million	https://minedocs.com/17/PureEnergy_ClaytonValley_PEA-2017.pdf
Clay Total			**4.28**	**117**		**2.6 billion**	
Brine Total			**0.36**	**1.52**		**38 million**	
Overall Total			**5.92**	**118**		**2.8 billion**	

Mt = millions of metric tons, LCE = lithium carbonate equivalent; to convert from LCE to contained lithium, divide the number by 5.323. EV equivalent is the number of electric cars that could be produced if all of the resources and reserves in a given project were extracted, assuming ~8 kg of lithium metal per vehicle (41.84 kg LCE[18]). The terms resources and reserves represent variations in the confidence of likely extraction of a given metal from a mineral deposit and are based on information provided by individual companies and collected but not reviewed by the Nevada Bureau of Mines and Geology. Reserves represent material that is considered to be economically extractable at the time of reporting, whereas resources only have a reasonable prospect for eventual economic extraction and recovery[19]. Reserves and resources are dynamic and can shrink and grow even during production, and confidence can either increase or decrease based on several variables[20]. As such, it is worth remembering that these are estimates with varying degrees of confidence.

Lithium deposits of two types are located in several areas of Nevada (figure 14), namely lithium-rich continental or salar brines and lithium-rich clay or sedimentary deposits. The state also contains the only lithium producing site within the U.S. in Clayton Valley, where Albemarle Corporation is currently extracting lithium from a continental brine reservoir, with extraction first started in 1966 (figure 14). Lithium-rich clay or sedimentary deposits are a relatively newly identified type of lithium deposit that probably relate to an interplay between volcanic activity and brines similar to those used for lithium extraction in Clayton Valley. The largest known lithium deposit in Nevada is located at Thacker Pass, 26 miles (42 km) southwest of the small town of McDermitt on the Oregon border (figure 14). This deposit is in the large 16 million-year-old McDermitt caldera-type volcano discussed later. Numerous other lithium-rich clay and sedimentary deposits are present in the caldera as well as in other areas, such as fault-bound closed hydrologic basins near Tonopah in west-central Nevada[21].

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[18] https://www.sciencedirect.com/science/article/abs/pii/B9780443185151000150

[19] https://pubs.geoscienceworld.org/segweb/segdiscovery/article/doi/10.5382/Geo-and-Mining-11/596384/Geology-and-Mining-Mineral-Resources-and-Reserves

[20] https://pubs.geoscienceworld.org/segweb/economicgeology/article/113/6/1235/565824/Growing-Global-Copper-Resources-Reserves-and

[21] https://pubs.nbmg.unr.edu/Geology-of-the-Tonopah-Lone-Mtn-p/b092.htm

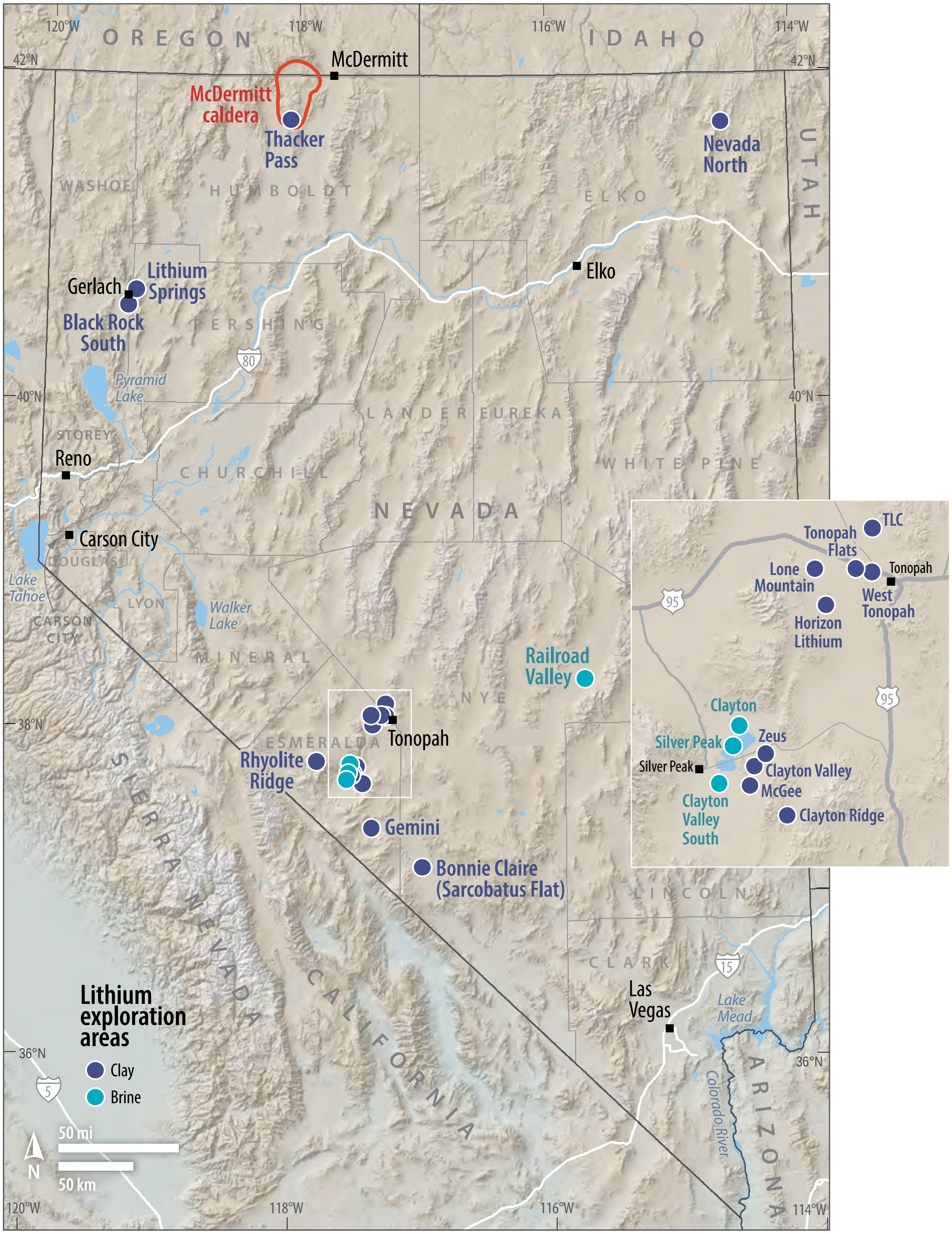

Figure 14. Map showing the geographic distribution of key lithium resources within Nevada.

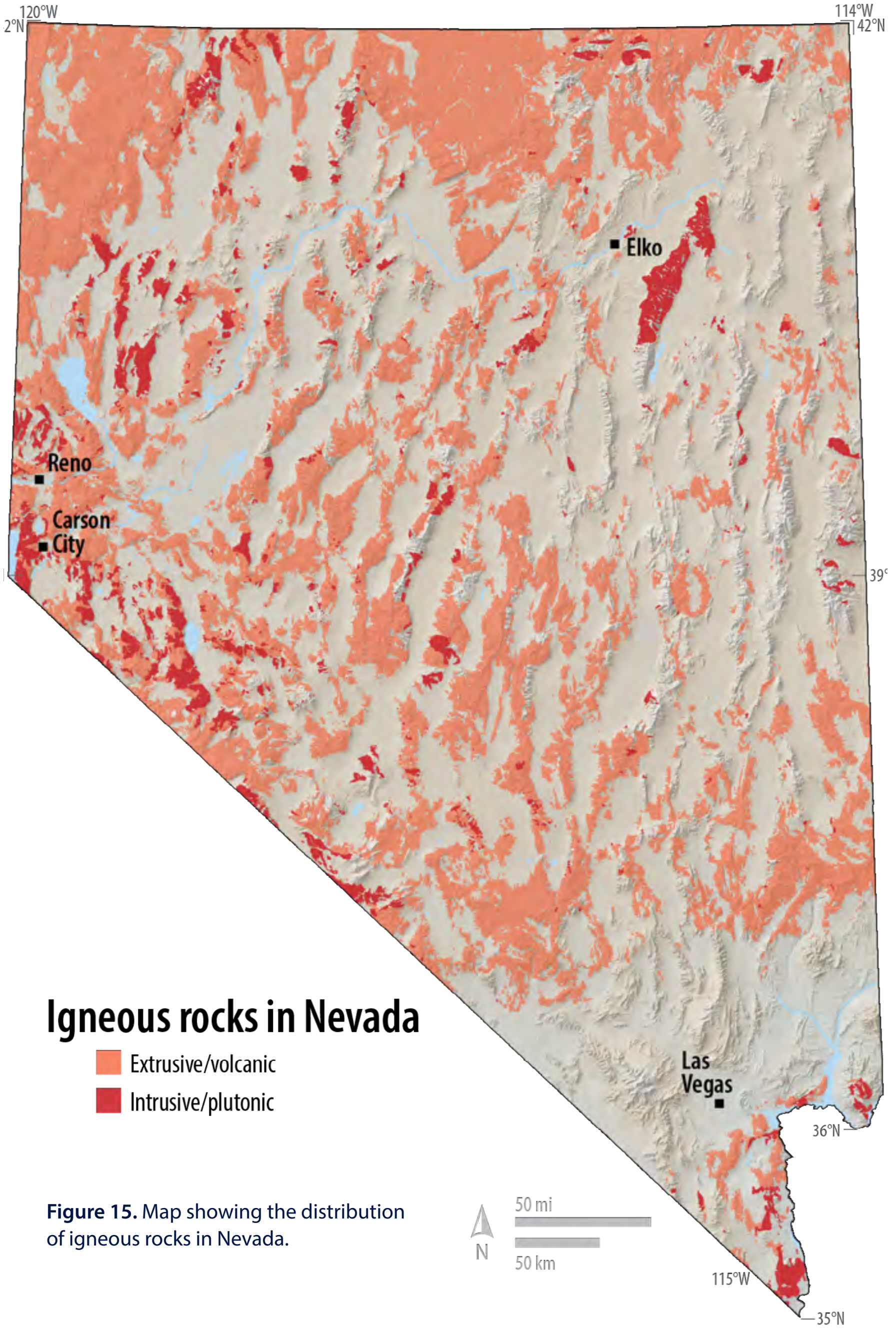

Figure 15. Map showing the distribution of igneous rocks in Nevada.

Volcanic Rocks

The lithium concentrated in the lithium-rich brines and lithium-rich clay deposits of Nevada is generally thought to have been derived from magma—molten rock—or the igneous rocks formed where magma cooled and solidified or erupted as ash from volcanoes at the Earth's surface. Nevada has large amounts of igneous rocks (figure 15), much of which formed from intense volcanic activity that began about 45 million years ago and has continued locally to almost the present day (the Lassen Peak eruption in 1915). This magmatic and volcanic activity occurred both at the Earth's surface and below, producing a range of different rock types. These include darker colored basalts similar to the lavas that erupt from Hawaiian volcanoes and rhyolites, which are typically lighter colored rocks that contain more silica (SiO_2) than basalt (figure 16, 17).

Extrusive or volcanic rocks

(cool quickly, small crystal sizes)

When the molten material (magma) reaches the Earth's surface and is erupted as lava or volcanic ash and other material.

Intrusive or plutonic rocks

(cool slowly, large crystal sizes)

These rocks form when the magma cools and solidifies underground.

Figure 16. Terminology used for igneous rock formation: extrusive or volcanic rocks form at the Earth's surface; intrusive or plutonic rocks form beneath the Earth's surface. Both form from magma, which at the Earth's surface is termed lava.

Figure 17. General examples of basalt (above) and rhyolite (right).
(Pannarai/Ekaterina/stock.adobe.com)

But what exactly are these igneous rocks?

Geologists commonly use the silica content of igneous rocks to distinguish and classify them. Basalts are dark and have about 50% silica. Rhyolites are typically light colored and contain 70 to 75% silica (figure 17; the ghost town of Rhyolite, west of Beatty, is named after the abundant rhyolite in the area). The lithium content of these igneous rocks also varies, with rhyolites generally containing significantly more lithium than basalts. For example, rhyolites typically contain 30 to 140 ppm (or parts per million) lithium versus less than 10 ppm for basalt. However, these concentrations do not tell the full story. Lithium is a very light element and is easily volatilized, meaning that the amount of lithium present in an igneous rock may be much less than in the magma that formed the rock. This is because volcanic eruptions involve the loss of dissolved volatile components like water, carbon dioxide, fluorine, and lithium, all of which are commonly released into volcanic gases during an eruption rather than becoming trapped in the rocks. This is similar to the carbon dioxide (CO_2) trapped in a can of soda that is shaken and then suddenly released. The lithium in a magma behaves in a similar fashion in that lithium goes along with the release of volatile components from a magma, meaning that the that the eventual solidified rock has much less lithium than the magma from which it formed, similar to the flat soda that has lost all of its dissolved CO_2.

It is actually possible, however, to estimate the amount of lithium that was present in magmas before their eruption or solidification. This technique uses tiny amounts of melt that are trapped as inclusions within crystals that formed before the magma solidified or erupted (figure 18). If these melt inclusions can be found, they can be analyzed to determine the pre-eruptive composition of a magma. Using this approach on rhyolites in Nevada suggests that the magmas that formed these igneous rocks commonly contained 1,000 or more ppm lithium prior to or during their eruption. This indicates that a lot of the lithium in these magmas was released before or during eruptions, either lost to the atmosphere during the lithium cycle or incorporated into fluids beneath the Earth's surface, potentially contributing to the brines used for lithium extraction today[22].

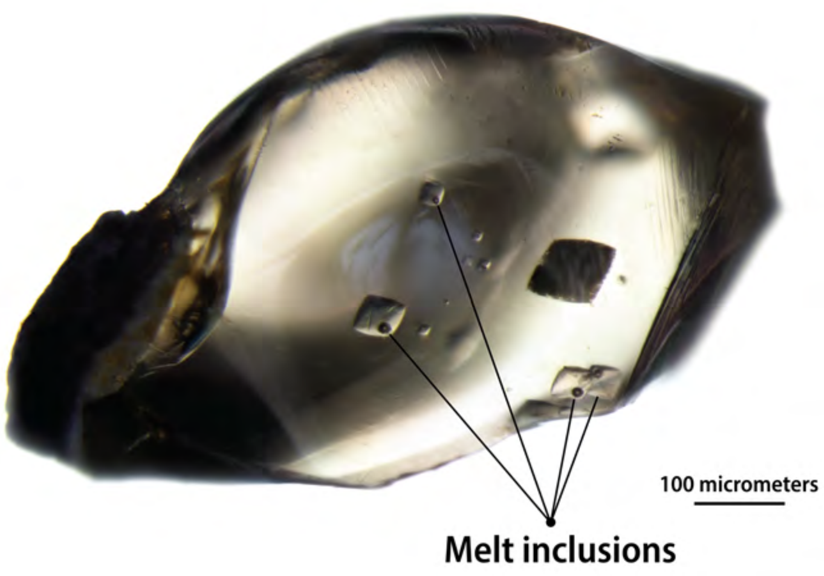

Figure 18. Image of microscopic melt inclusions within a crystal of quartz; these inclusions represent small trapped parts of the melt or magma that formed the quartz and the associated igneous rock that can be used to estimate the lithium content of the original magma. Photograph by Kathryn Watts, U.S. Geological Survey, Spokane, Washington.

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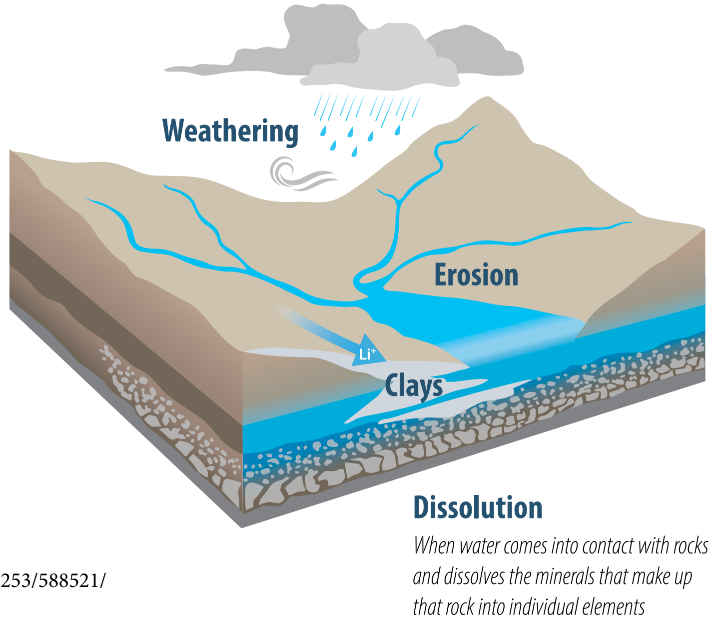
[22] https://pubs.geoscienceworld.org/segweb/economicgeology/article/108/7/1691/128537/Silicate-Melt-Inclusion-Evidence-for-Extreme-Pre

Photograph by Chip Carroon.

Lithium in Clays and Sedimentary Rocks

One of the main processes involved in the mobilization and concentration of lithium in sedimentary rocks and clays is weathering and dissolution (figure 19). The lithium present in rocks on Earth's continents is redistributed during weathering into lithium in solution in rivers, groundwater, or in fluids in pores in sedimentary rocks, or into secondary weathering products like clays, oxide minerals, or zeolites. Clays are unusual in that they commonly contain 10s to 100s of ppm of lithium[23]. This means that a considerable amount of the lithium present in the rocks on Earth, including the volcanic rocks mentioned previously, end up in secondary minerals like clays after the original rocks are weathered and eroded away. Clays can also form on the seafloor by seawater-related alteration of rocks of the oceanic crust. The clays formed during this process contain lithium extracted from seawater. In summary, several processes can take a lithium-rich source material, such as volcanic rocks and magmas, and concentrate lithium in the resulting clay or sedimentary rock.

Figure 19. Key processes in the mobilization and addition of lithium to water and sedimentary units such as clays.



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[23] https://pubs.geoscienceworld.org/msa/elements/article/16/4/253/588521/Lithium-and-Lithium-Isotopes-in-Earth-s-Surface

Photograph by Jim Faulds.

Lithium in Groundwater

Lithium concentrations in groundwater vary because of different environmental conditions but are typically very low (less than 0.04 ppm)[24], with higher lithium concentrations (up to 1.86 ppm) identified in groundwater from domestic wells in the western Great Basin[25]. Groundwater that is enriched with dissolved solids, known as "brines", may contain lithium dissolved from the surrounding environment. These brines can have high lithium concentrations (from 160 to higher than 1,400 ppm)[26], as the elevated temperature (compared to, for example, seawater) and presence of other dissolved elements in these fluids increase the solubility of lithium. These brines are also the source of the lithium in the deposit at Clayton Valley as specifically discussed later in this report.

Nevada and other parts of the Great Basin have a natural environment that favors the formation of lithium-rich groundwater (figure 20). This is caused by a number of factors, including:

1. an arid climate;
2. the presence of closed basins containing a saline lake and/or salt flat/playa;
3. the natural horizontal extension (spreading) and subsidence (sinking) of the Earth's crust as a result of ongoing broad-scale tectonic and geological activity;
4. volcanic and/or geothermal activity;
5. suitable lithium-bearing sources; and
6. older groundwater with sufficient time to concentrate a brine (figure 20).

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[24] https://www.sciencedirect.com/science/article/pii/S0147651308000742

[25] https://www.sciencedirect.com/science/article/pii/S0048969722053761?via%3Dihub

[26] https://pubs.usgs.gov/publication/pp1802K

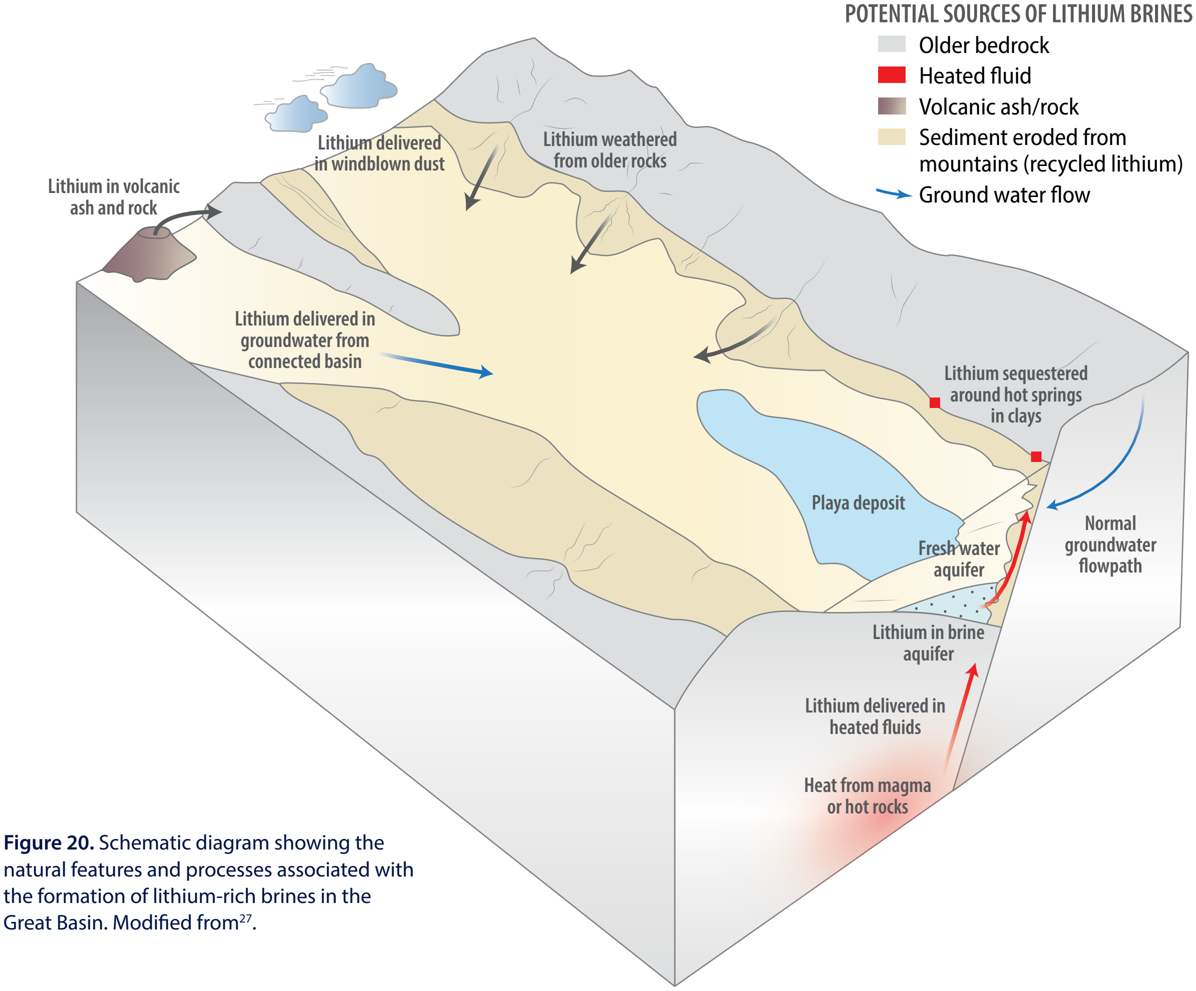

Figure 20. Schematic diagram showing the natural features and processes associated with the formation of lithium-rich brines in the Great Basin. Modified from[27].

The geography of the Great Basin also contributes to the abundance of lithium. Many of the region's valleys are lithium-rich, because they are hydrologically "closed basins", where surface water can flow in but not out. Rain and snowfall, which may contain very low levels of dissolved lithium, collect in mountain-ringed valleys and percolate through permeable rock and soils, dissolving more lithium on the way to recharging groundwater aquifers. Groundwater moves slowly to the valleys from the mountains, which promotes physical and chemical interactions that increase lithium concentrations. Lithium-rich groundwater can also flow into low elevation basins and accumulate there, as is the case in Clayton Valley.

The regional geological setting of the Great Basin further contributes to generating lithium-rich deposits. Regional crustal extension has produced many low valleys or depressions at the Earth's surface that have filled with sediment eroded from the surrounding mountain ranges. The regional extension and thinning of the crust have also induced relatively high thermal gradients (rate at which temperature increases with depth) and geothermal activity. The resulting warmer groundwater temperatures can enhance leaching of lithium from surrounding rocks. In addition, volcanic activity was widespread in the past (millions of years ago), and some of these older volcanic rocks provide a ready source of lithium. Furthermore, the high temperature gradients can facilitate convection and circulation of groundwater, pushing it from deeper lithium-source areas (volcanic rock, clays, or solidified magma chambers) to the brines at and near the ground surface.

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[27] https://pubs.geoscienceworld.org/segweb/books/edited-volume/1998/chapter/16276487/Lithium-BrinesA-Global-Perspective

Figure 21. Dixie Valley geothermal field. Photograph by Bridget Ayling.

Figure 22. Dixie Valley geothermal plant. Photograph by Bridget Ayling.

Lithium in Geothermal Waters

The natural geothermal waters in Nevada are currently used to generate a significant amount of geothermal energy (figures 21 and 22) but may also represent potential sources of lithium. Geothermal energy, derived from the Earth's internal heat, has long been recognized as a renewable energy resource with vast potential in the Great Basin. In Nevada, the intersection of geothermal and lithium resources offers a promising avenue for sustainable energy production and mineral extraction. Significant lithium resources are known to be present in other geothermal systems, especially those associated with active volcanism and brines in the Salton Sea area in California. Although geothermal systems in Nevada are generally not related to volcanism and typically contain less lithium than lithium-enriched brines in the state, they still remain prospective targets for lithium extraction.

Nevada's geothermal resources are rooted in the tectonic processes that have shaped the region over millions of years. The Great Basin's complex geology, characterized by faults, regional extension, and crustal thinning, provides optimal conditions for formation of geothermal reservoirs.

Geothermal reservoirs in Nevada are typically controlled by active faults accommodating the crustal extension. These faults help to channel hot fluids from deeper levels in the crust to relatively shallow levels (typically 0.5 to 1.5 miles or 1 to 2 km below the surface), allowing for commercial development. These geothermal reservoirs consist of permeable subsurface rocks through which fluids heated by the Earth's internal heat can flow readily. As rainwater and snowmelt seep into the ground, they percolate through fractured rock to deeper levels, where they are heated and pressurized and can, in some cases, rise back to the surface as hot springs, geysers, or steam vents. The heat and pressure within these reservoirs create ideal conditions for the formation of mineral deposits, including lithium. The lithium within these systems is thought to be derived from rocks with which the hot water interacts. These rocks are either located within the subsurface or are weathered and eroded at the surface. This process mobilizes lithium into groundwater. The groundwater is then sufficiently heated by the high geothermal gradient to locally generate lithium-enriched geothermal systems that can be used for energy generation. Figure 23 shows lithium concentrations measured in geothermal brines across the state, which range from 0 to over 75 ppm. The highest geothermal lithium concentrations in Nevada have been identified in Lander County, close but unrelated to the geothermal waters that power the largest geothermal power station in Nevada, McGinness Hills.

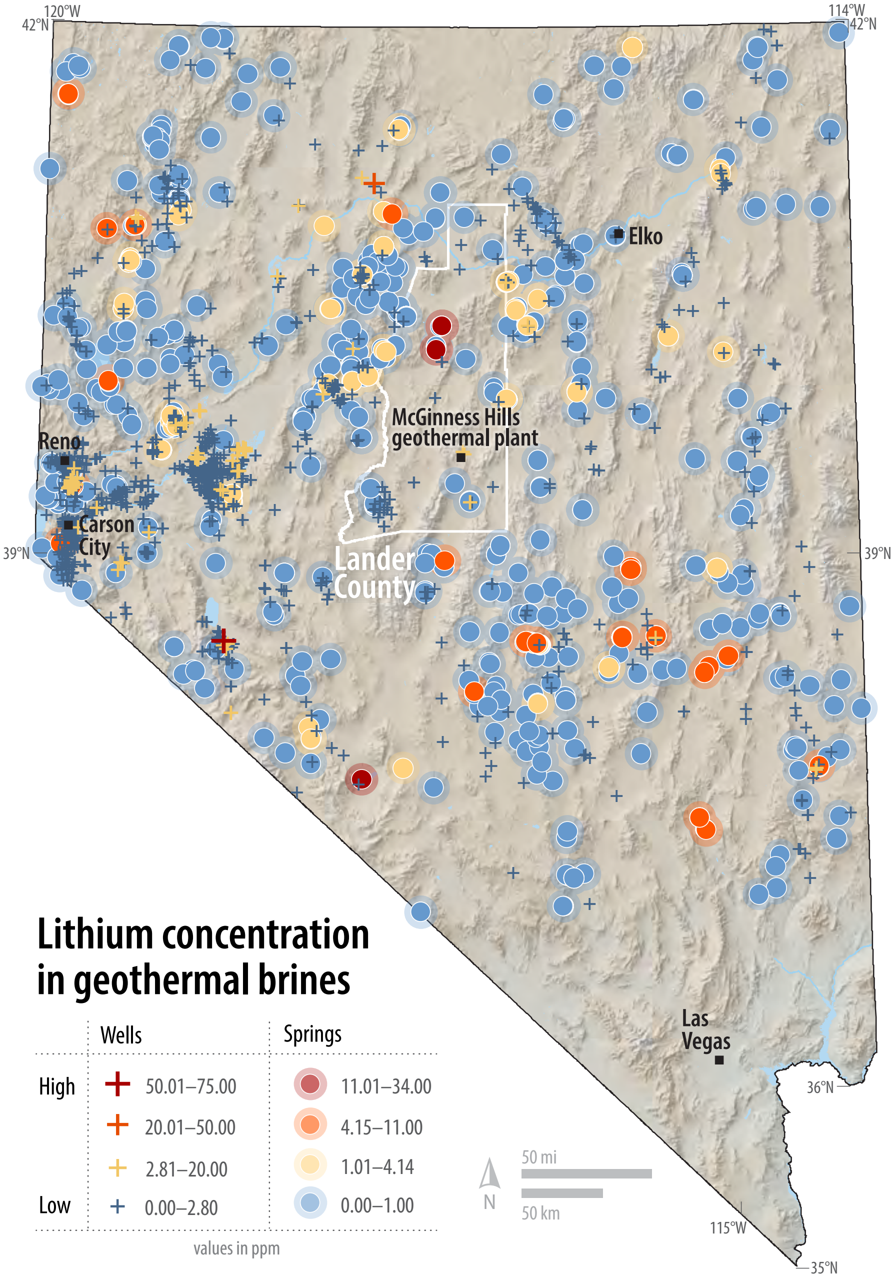


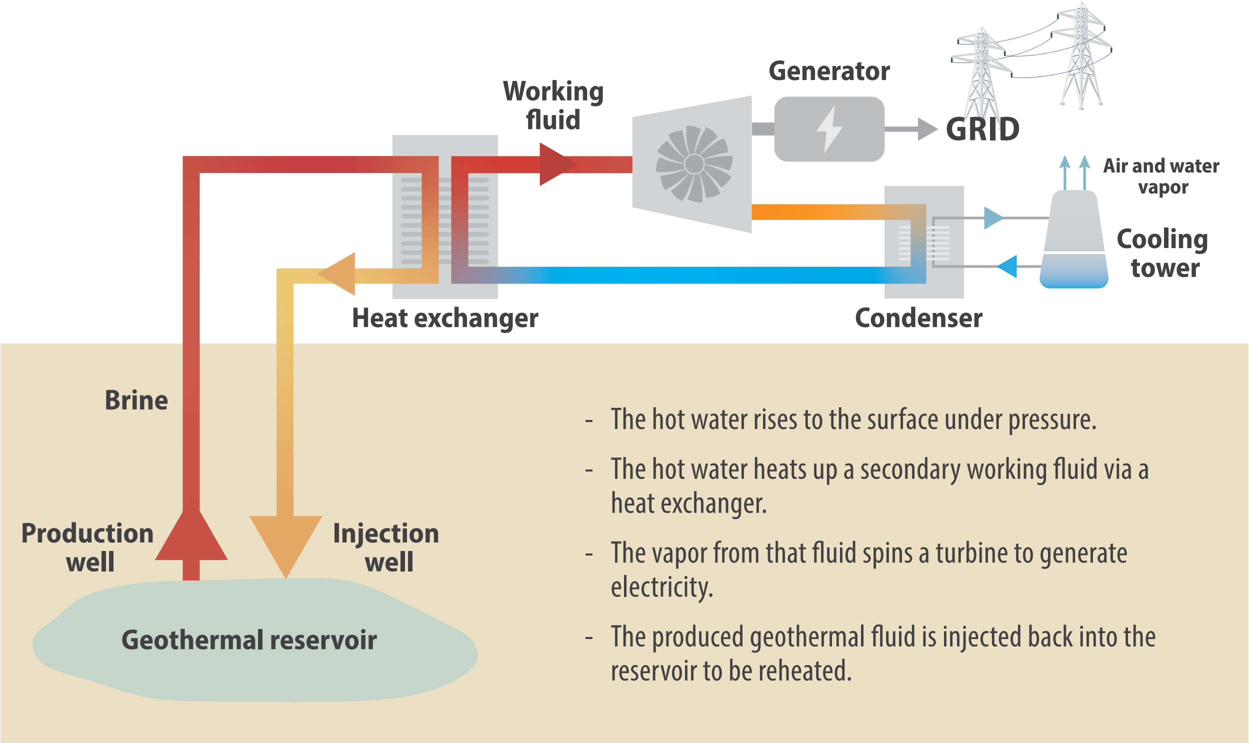
Figure 23. Lithium concentrations (ppm) in geothermal brines in Nevada.

Although some geothermal fluids are known to have elevated concentrations of lithium, extracting this lithium while not impacting potential energy generation remains problematic. However, the convergence of geothermal activity and lithium resources in Nevada has significant economic potential, especially if lithium extraction can be combined with existing geothermal infrastructure, such as power plants and well networks, which reduce the capital costs and environmental footprint of lithium extraction operations. The economic viability of lithium extraction from geothermal brines hinges on several factors, including lithium concentration, extraction efficiency, market prices, and regulatory frameworks, all of which are being actively investigated by researchers at the Center for Research in Economic Geology at the Nevada Bureau of Mines and

Geology. Lower lithium concentrations or inefficient extraction methods could increase production costs and limit the competitiveness of lithium projects from geothermal reservoirs in Nevada.

From an environmental perspective, the extraction and processing of lithium from geothermal brines poses certain challenges and considerations. Although geothermal brines offer a relatively low-impact source of lithium compared to traditional hard-rock mining methods, they still require careful management to mitigate potential environmental impacts. Disposal of brine by-products, such as salts and wastewater, must also be managed to prevent contamination of surface and groundwater resources. However, nearly all geothermal facilities in Nevada are "closed loop", meaning all produced fluid is returned to the geothermal reservoir well below the surface, thus mitigating the need for wastewater disposal (figure 24).

Nevada's rich geological endowment of geothermal activity and lithium resources presents a rare opportunity for sustainable energy production and mineral extraction within the U.S. The symbiotic relationship between geothermal brines and lithium deposits underscores the interconnectedness of Earth's geological processes and the potential for innovation in resource use.



- The hot water rises to the surface under pressure.
- The hot water heats up a secondary working fluid via a heat exchanger.
- The vapor from that fluid spins a turbine to generate electricity.
- The produced geothermal fluid is injected back into the reservoir to be reheated.

Figure 24. Schematic diagram showing the setup of a typical geothermal energy plant. The brines that are used in the power generation shown here are also a potential source of lithium and other metals.

Importance of Structural Setting in Lithium Deposit Formation

The formation of lithium deposits requires the confluence of several different geological factors and processes. In Nevada, numerous closed hydrologic basins are essential to trap lithium in both brine and clay/sedimentary deposits. These structural basins are formed as a result of faulting relating to tectonic activity and the extension of the crust (figures 25 and 26). These tectonic forces mean that the state of Nevada is essentially expanding east-west by about two basketball courts per year[28]. These forces cause rocks to break apart along normal faults that lower one area of land relative to an adjacent area of land in a process related to extension and tectonic forces that pull an area apart. Over many thousands to millions of years, these normal fault-related depressions can become significantly deep and fill with sedimentary materials derived from adjacent areas. These processes have formed many of the closed basins within Nevada. Other processes include strike-slip movements, where rocks are moving laterally side by side relative to each other (as is the case for the famous San Andreas fault system). Strike-slip motion is currently occurring in western Nevada and eastern California in addition to crustal extension.

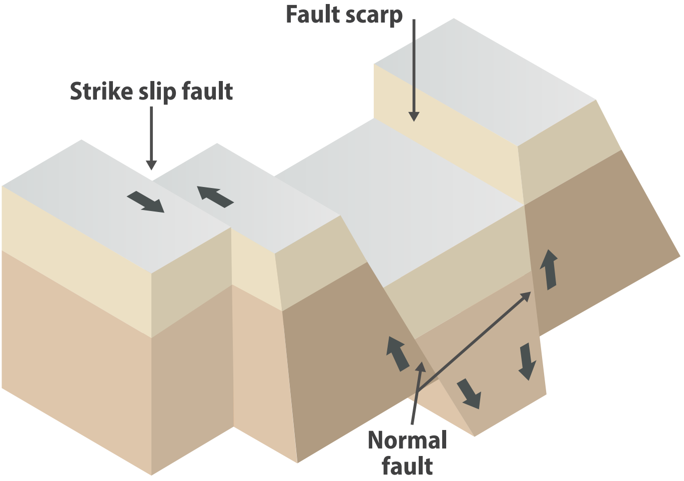


Figure 25. Different types of faults, where strike-slip faults move rocks past each other, and normal faults are formed by extension, or rocks being pulled apart.

Figure 26. High-angle normal fault cutting Rhyolite Ridge tuff. Photograph by Mike Darin.

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[28] https://pubs.nbmg.unr.edu/Geod-strain-rate-full-size-p/m178.htm

Most normal faulting in the Great Basin began around 17 million years ago and over time has generated numerous closed basins. Normal and strike-slip faulting that continues today disrupted some of the early-formed basins and created new ones, meaning that Nevada and parts of adjacent states consist almost entirely of closed basins separated by mountain ranges. This has led to the use of the term Basin and Range Province to describe this region, with the Great Basin forming part of the larger Basin and Range Province. Erosion of the ranges over time has generated sediments that accumulated in the basins to thicknesses as great as 3 miles (5 km).

Other types of basins are also present within Nevada, including closed basins that formed at the sites of very large volcanoes. These large volcanoes are commonly called "supervolcanoes", including the well-known example at Yellowstone National Park[29]. In a supervolcano, a large body of magma forms a "magma chamber" that underlies the volcano at depths of a few to 6 miles (up to 10 km; figure 27A). As the magma rises to the surface, some combination of fracturing of the Earth's surface above the volcano, depressurization of the magma as a result of its ascent, and an increase in the volatile content of the magma causes the magma to erupt explosively. Well-studied calderas in the U.S. and worldwide are known to have erupted 100s to 1,000s of cubic kilometers of magma. Some of this erupted rhyolite magma flows away from the caldera in devastating mixes of hot volcanic particles (volcanic ash), volcanic gas, and fragments of surrounding rocks. These "pyroclastic flows" are the most hazardous form of volcanic eruptions (figure 27B). The 1980 eruption of Mount St. Helens in Washington State was a tiny example (approximately 0.23 cubic miles or 1 cubic km) that devastated a significant area, as was the eruption of Mount Vesuvius in Italy that buried the Roman towns of Pompeii and Herculaneum. Even more of the erupted magma can accumulate in significant thicknesses within the caldera depression (figure 27C), with one example being the McDermitt caldera's pyroclastic flow deposit, which is as much as 1,640 feet thick (500 m).

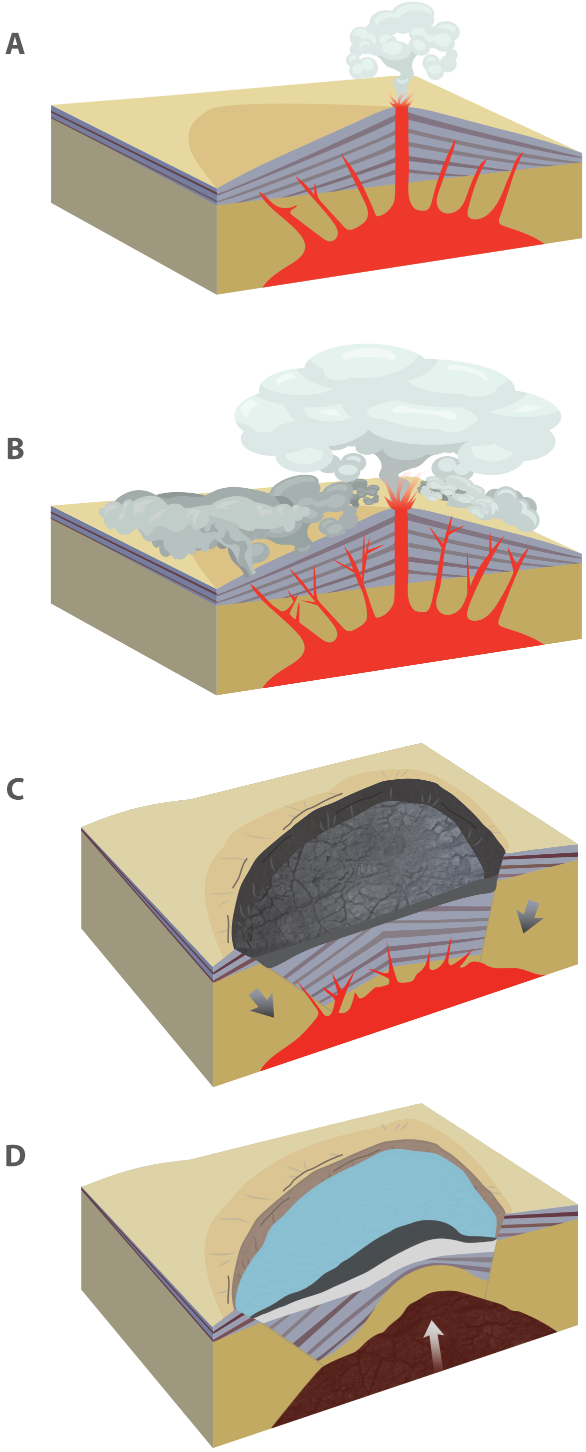

Figure 27. Stages of caldera formation: **A.** Small volumes of magma erupt quietly from a chamber beneath the surface to generate lavas. **B.** Gas pressure in the magma increases so that huge volumes of magma begin to erupt explosively as pyroclastic flows. **C.** The evacuated space is unstable and collapses to make a caldera, a large, generally circular depression. **D.** Lakes almost always fill the caldera after eruption.

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[29] https://en.wikipedia.org/wiki/Yellowstone_Caldera; https://www.usgs.gov/observatories/yvo

If nothing else happened, these large eruptions would generate a giant cavern in the former magma chamber, as the magma that occupied it erupted to form volcanic ash, rocks like the rhyolites associated with lithium in Nevada, and other volcanic and igneous rocks. However, the overlying rocks above such a giant cavern are not strong enough to sustain this cavern, causing a commonly cataclysmic downward collapse that generates a roughly circular depression. Over time, these depressions can form closed basins called "calderas", from the Spanish word for a similarly shaped cooking pot (figure 27C, D). Known calderas in Nevada are typically 6–24 miles (10–40 km) or more in diameter (figure 28), including the McDermitt caldera, a significant area of lithium mineralization in the northern part of the state directly west of the town of McDermitt. Even with this collapse, in many cases considerable magma can remain in the chamber after eruption. This magma can continue to rise, pushing up the caldera floor into a "resurgent dome" (figure 27D), although this uplift is less than the original collapse, allowing the resulting calderas to remain as closed basins. This magma can also lead to continued volcanism in the caldera and in other volcanoes in the region that can generate large amounts of volcanic ash. Much of this ash gets deposited in the caldera as units typically known as "intracaldera tuffaceous sediments". The volcanic ash also accumulates in the surrounding area, especially within structural basins formed by normal faulting. Rhyolite ash is generally enriched in lithium and is one potential source of lithium for deposits in both structural and caldera basins. Large lakes also typically form (figure 27D), with notable examples from relatively recent volcanic eruptions at both Yellowstone National Park in Wyoming and Crater Lake National Park in Oregon. Examples of present-day lakes in structural

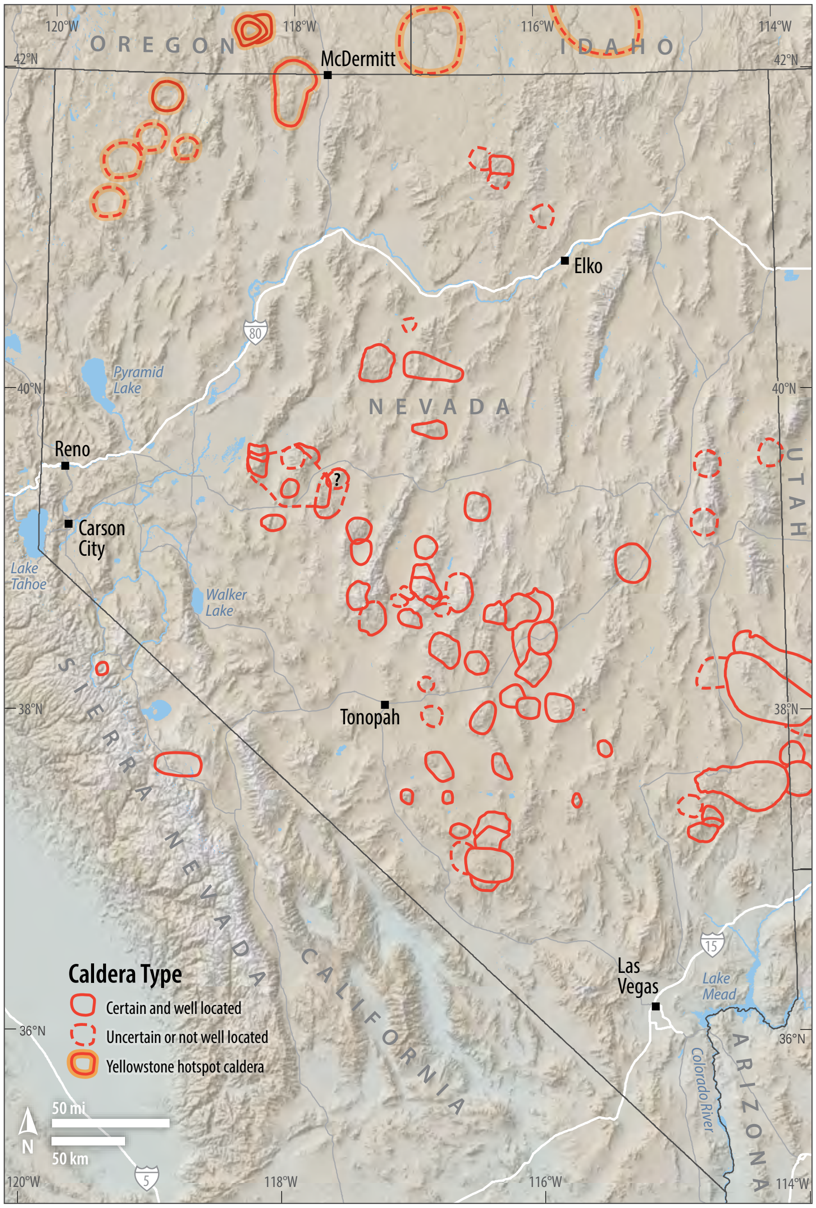

Figure 28. The geographical distribution of calderas in Nevada and the wider Great Basin (from research by Nevada Bureau of Mines and Geology geologists[30]). Although calderas are ideal environments to contain lithium mineralization, commercially viable lithium mineralization has only been found in the McDermitt caldera to date.

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[30] https://pubs.geoscienceworld.org/gsa/geosphere/article/9/4/951/132695/Magmatism-ash-flow-tuffs-and-calderas-of-the

basins not associated with volcanism include Lake Tahoe in California and Nevada, Pyramid and Walker Lakes in Nevada, and the Great Salt Lake in Utah. Nevada's arid climate means that many lakes that originally formed in these fault-bound basins have dried up, leaving lake sediments that can be enriched in lithium or brines trapped within the lake sediments and ash deposits.

The dramatic history of crustal extension over the last 17 million years and caldera-forming super-eruptions over the last 40 million years has endowed Nevada with a multitude of closed basins (figure 28). The common occurrence of both types of hydrologically closed basins means that the entire state of Nevada is highly prospective for lithium exploration.

Although closed basins and evaporation are significant factors in potentially concentrating lithium, not all closed basins are likely to contain lithium. Two examples of modern, closed basins in Nevada that demonstrate this are Pyramid and Walker Lakes in western Nevada (figure 29). Both are fed from rivers that drain the eastern Sierra Nevada, namely the Truckee and Walker Rivers, respectively. Notably, neither Pyramid Lake nor Walker Lake have significant amounts of lithium, either dissolved in lake water or in sedimentary deposits in the lakes. The key difference between these lakes and closed basins that contain lithium brine or clay/sedimentary deposits, such as Clayton Valley, is the paucity of rhyolitic ash in the Pyramid and Walker Lake drainage areas. These areas may have transport mechanisms for lithium and potential traps in the form of closed basins but lack a source of lithium. This lack of rhyolite ash and lithium deposits demonstrates the need for a source of lithium in the recipe to generate a lithium mineral deposit.

Figure 29. Drainage systems of the western Great Basin, showing the inputs to Pyramid and Walker Lakes. The Truckee and Walker Rivers flow to Pyramid and Walker Lakes, respectively. Although the lakes are closed hydrologic basins, which are ideal to form lithium mineralization, no deposits occur there, probably because they lack abundant rhyolite ash in their drainage areas.

Making of a Lithium Deposit

- ✓ Lithium Source
- ✓ Transport of Lithium
- ✓ Lithium Trap

Remember, you need these three things for a successful lithium deposit!

Lithium Resources in the Great Basin and Nevada

This section summarizes:

1. important known lithium exploration regions in Nevada,
2. significant deposits in those regions,
3. key geological characteristics of these deposits and regions, and
4. their history of exploration and production, all to document potential future sources of Nevada lithium production.

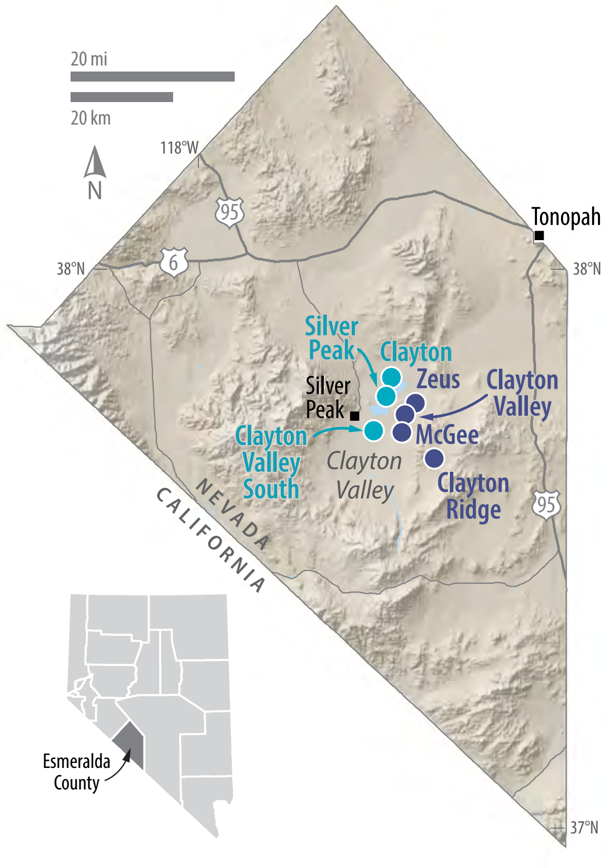

Figure 30. Location of Clayton Valley brine (light blue) and clay (dark blue) operations and exploration.

Clayton Valley Brines and Clays

Clayton Valley is an arid, closed basin located in Esmeralda County, Nevada, that covers an area of approximately 500 square miles (1,300 square km) and is known to contain significant amounts of lithium[31,32], (table 1 and figure 30). Although other valleys within the Great Basin also contain lithium-rich brines, Clayton Valley hosts the only operating primary lithium production facility in the U.S., known as Silver Peak. Silver Peak is currently operated by Albemarle Corporation and has been in operation since 1966, producing approximately 5,000 metric tons of lithium carbonate equivalent or 1,000 metric tons of contained lithium per year, with plans to double production in the near future. The increasing demand for lithium has led to increased amounts of exploration for lithium brines and clays in Clayton Valley, with nearly 5,400 lithium claims[33] and projects proposed by approximately 30 companies[34].

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[31] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021GC009916

[32] https://images.water.nv.gov/images/publications/recon%20reports/rpt45-clayton_valley_stonewall_flat.pdf

[33] https://data-ndom.opendata.arcgis.com/pages/ndomdatagallery

[34] https://minerals.nv.gov/uploadedFiles/mineralsnvgov/content/home/features/RP/RP_NWRA_NDOM_20230130.pdf

Clayton Valley is a large closed basin formed by movement on normal faults that accommodate stretching of the crust. The basin is filled with intermingled layers of volcanic rock and ash, sediments, and evaporite minerals. The playa within the valley has a hard, dry surface, or "crust," formed by salts left behind after lake water has evaporated (figure 31). The valley is surrounded by other, topographically higher closed basins with the groundwater resources and subsurface flow in and around the valley having been studied extensively by the Nevada Division of Water Resources, the U.S. Geological Survey, and others[35,36,37,38,39]. Some, but not all, of these studies suggest that groundwater commonly flows from higher basins into Clayton Valley through the subsurface, which indicates that the groundwater drainage area for Clayton Valley is much larger than the topographic valley. Figure 32 shows a possible maximum groundwater drainage area, which has important implications for the possible source of lithium in the producing brine. One example of this is the fact that the suggested more extensive drainage basin includes a large area west of Tonopah that contains significant lithium-clay deposits. Leaching from these deposits could contribute to the lithium in brines in Clayton Valley. Whatever the source of lithium in the valley, the dissolved lithium within brines in the basin is thought to be derived from weathered sedimentary or volcanic material with high lithium concentrations and is likely continuously enriched by geothermal fluids. The Clayton Valley basin primarily receives water as runoff from the surrounding mountains via ephemeral, small creeks that are almost always dry. This water subsequently evaporates within the closed basin setting (figure 33), leaving concentrated lithium brine behind.

Figure 31. Typical environment in the Clayton Valley region showing the Silver Peak lithium brine operation, looking southeast. The blue waters are brines that have been pumped to the surface for evaporation to concentrate lithium before processing to precipitate lithium carbonate. Photograph by Mike Ressel.

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[35] https://pubs.nbmg.unr.edu/Forum-on-Geology-of-Industrial-p/sp033.htm

[36] Kunasz, I.A., 1970, Geology and geochemistry of the lithium deposit in Clayton Valley, Esmeralda County, Nevada: The Pennsylvania State University, State College, PA, Ph.D. thesis.

[37] https://www.gsnv.org/shop/possible-volcanic-source-of-lithium-in-brines-in-clayton-valley-nevada/

[38] https://www.researchgate.net/publication/258466861_Origin_and_Evolution_of_Li-rich_Brines_at_Clayton_Valley_Nevada_USA

[39] https://water.nv.gov/library/water-planning-reports

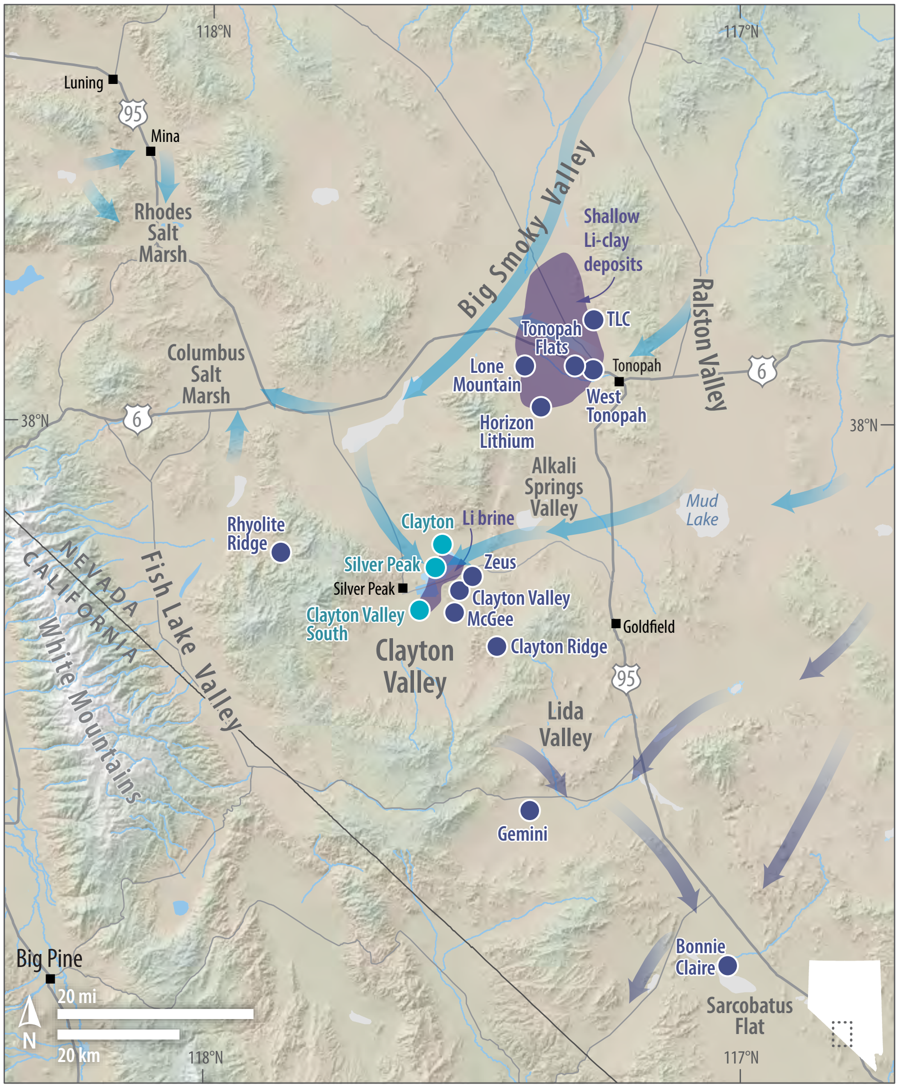

Figure 32. Schematic groundwater flow within the Tonopah–Clayton Valley–Sarcobatus Flat region showing the location of lithium mineralization. Groundwater flow from [39].

Figure 33. Typical playa environment showing desiccation cracks and the evaporation-dominant climate within these regions. Photograph by John Muntean.

Figure 34. Silver Peak lithium mine. Photograph by Scott Thibodeaux.

At Silver Peak (figure 34), lithium is extracted from the brine using a method commonly used with continental or salar brine lithium operations elsewhere called “evaporative concentration” (shown in figure 35A). This involves pumping brines from aquifers into shallow artificial ponds for open-air evaporation. Brine is pumped from multiple wells in six different aquifers and then passed through a series of nine ponds to evaporate water, concentrate lithium and precipitate other dissolved minerals, including salt (sodium chloride), for removal. An onsite chemical plant then precipitates lithium carbonate and lithium hydroxide. Using this method, Silver Peak withdraws about 3.8 billion gallons of brine per year[41], producing around 5,000 metric tons of lithium carbonate equivalent per year[42]. In general, the evaporative concentration process is considered cost-effective compared to other lithium extraction methods, but potential drawbacks include:

1. a lengthy timeframe (typically 18 to 24 months) to complete the concentration stages;
2. the loss of a significant amount of water to evaporation;
3. potential contamination of shallow groundwater from waste material leakage through the bottom of the evaporation pond[42];
4. the process is not easily scaled up; and
5. the evaporation ponds themselves require a significant amount of space, creating potential land-use and environmental conflicts for other brine development.

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[41] https://pubs.acs.org/doi/10.1021/acsestengg.1c00244

[42] McKenna, S., Hoekman, S.K., Lutz, A.D., Gentilcore, D.M., 2022, Lithium opportunities and challenges in Nevada: Desert Research Institute, DRI Publication Number 41290.

Another extraction process is being tested across the U.S., including at Clayton Valley, with geothermal brines in the Salton Sea area of California, and with oilfield brines of the Smackover Formation in Arkansas and Texas. However, it has not been implemented at the industrial production scale in the U.S. Known as "Direct Lithium Extraction", this process uses advanced technologies rather than evaporation and involves the chemical and/or physical separation of lithium from brines using a range of methods that may include solvent extraction, ion exchange, filtration, or sorption[43] (illustrated in figure 35B). Lithium-enriched brines are pumped to the surface and directed to a Direct Lithium Extraction processing plant that extracts the lithium before returning the brine back to the aquifer. Relative to evaporative concentration, Direct Lithium Extraction may be able to quickly process larger amounts of lithium, while conserving water by returning used brine to the aquifers. A recently authorized Direct Lithium Extraction pilot plant in Clayton Valley is expected to provide the first attempt with the new extraction technology in Nevada[44].

As previously described, the lithium-rich brines found in the Great Basin and exemplified in Clayton Valley are typically located in arid basins with natural water deficits, overallocations, and with difficult to obtain water rights, which raises some concerns about the potential water-resource impacts of lithium extraction facilities. Additional concerns include the environmental impacts associated with land disturbances, energy use, chemical additives, and waste disposal—issues deserving attention when considering future lithium operations in Nevada and the Great Basin. A guide for stakeholders to identify and recognize potential impacts on water resources is presented in "Identifying Potential Hydrologic Impacts of Lithium Extraction in Nevada," a 2023 report by researchers at the Desert Research Institute in Reno and Las Vegas. Further information on the regulation of waters, including these brines, is available in the Nevada Revised Statutes, including NRS 445A and 519A[45].

Clayton Valley also has lithium-clay deposits that are being explored (table 1), because the valley has all three requirements to be considered prospective for clay/sedimentary lithium deposits: lithium sources, transporting processes, and a location to trap the lithium, with the concentration of this lithium enhanced by evaporation of the transporting fluids or brines. The source includes both abundant local rhyolitic ash (related to the 7- to 5-million-year-old rhyolites around this region) and upstream lithium mineralization (such as the lithium clay/sedimentary deposits of the Siebert Formation to the west of Tonopah, another emerging area of lithium exploration).

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[43] https://www.nature.com/articles/s43017-022-00387-5

[44] https://www.dri.edu/project/potential-hydrologic-impacts-of-lithium-extraction/

[45] leg.state.nv.us/nrs/

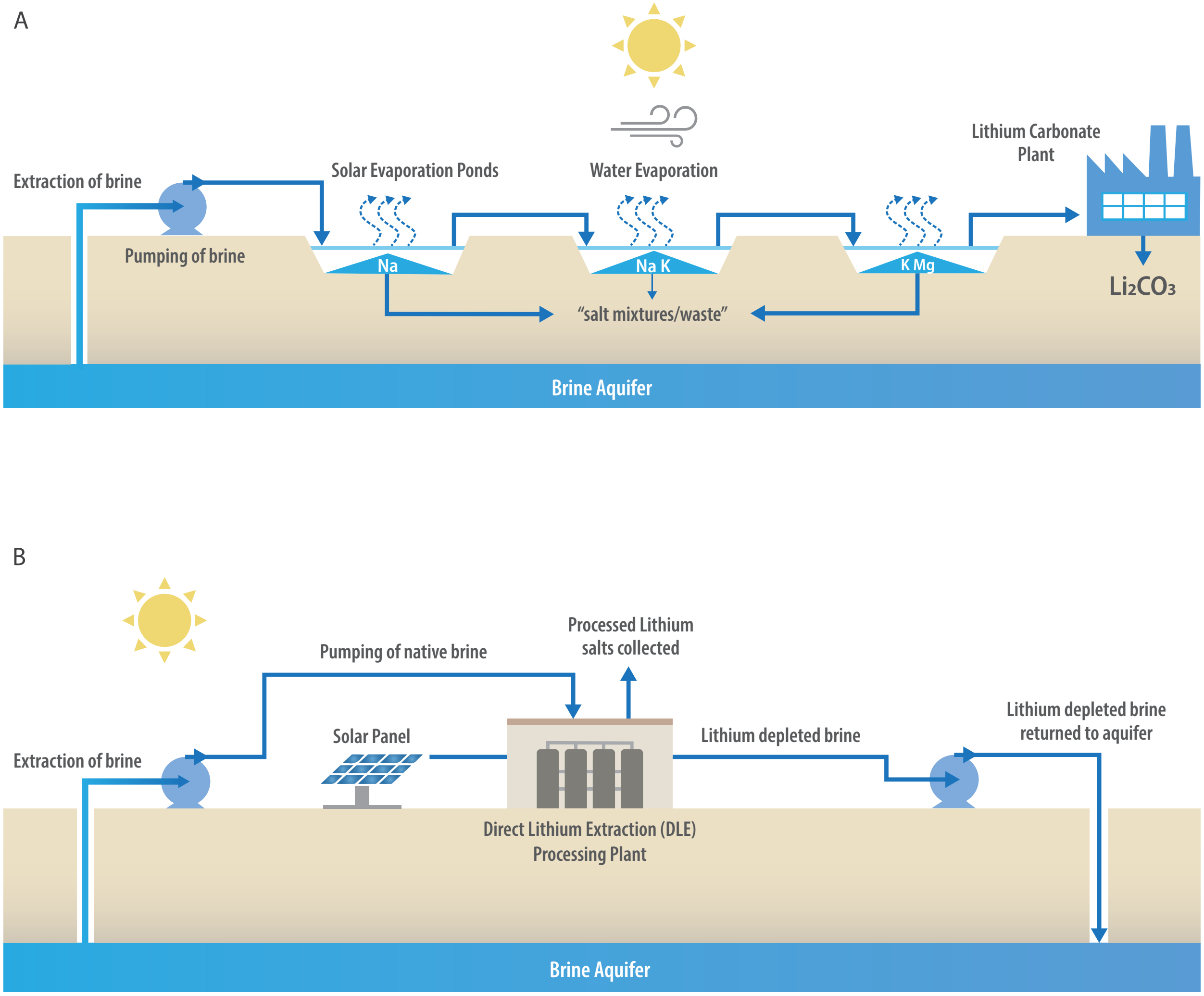

Figure 35. Schematic of the general processes for extracting lithium from brines using, **A.** evaporative concentration method, and **B.** direct lithium extraction. At different stages of evaporative concentration, different salts are precipitated. Modified from [46].

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[46] https://pubmed.ncbi.nlm.nih.gov/29929287/

McDermitt Caldera Lithium Clay Resources

The McDermitt caldera (figure 36) contains the largest known lithium clay/sedimentary deposits in Nevada and potentially the world[47,48]. The Thacker Pass project within the caldera is one of the largest known lithium resources in the U.S. The caldera marks the beginning of the "Yellowstone hotspot" (figure 37), a belt of volcanism and magmatism between the caldera and the present-day Yellowstone region[49]. This volcanism and magmatism migrated northeastward as the North American plate moved relatively southwest over a large heat source in the mantle that drives the magmatic and volcanic activity in this area. The active volcanism at Yellowstone (including calderas) is the youngest evidence of this magmatic activity.

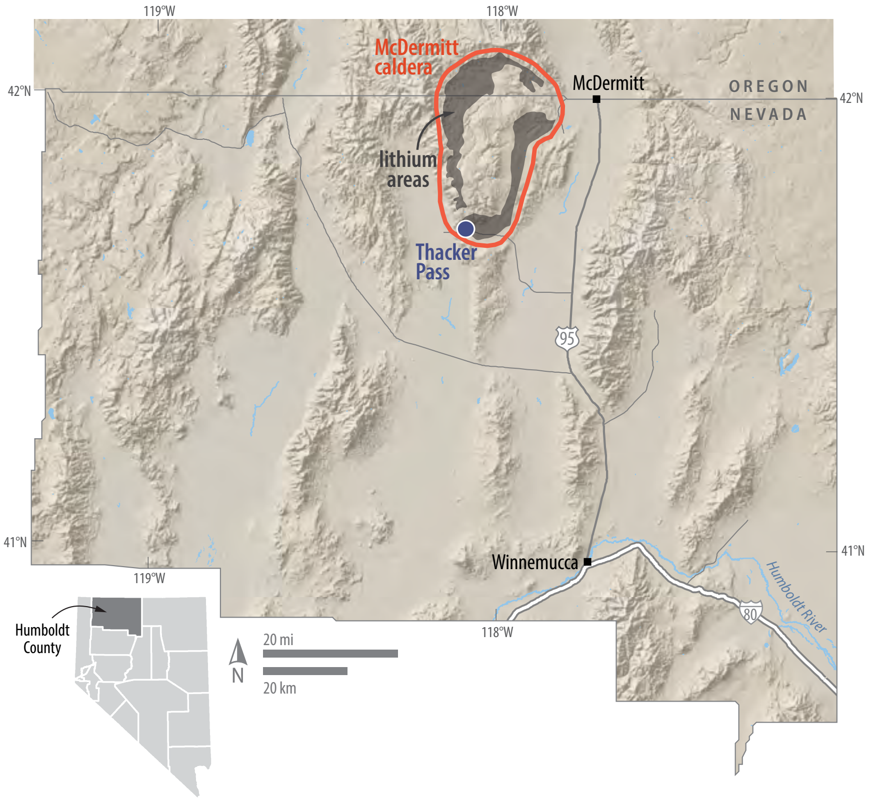

Figure 36. Location of the McDermitt caldera in northern Nevada and southern Oregon with shading indicating areas of known lithium clay/sedimentary mineralization, potentially some of the largest lithium deposits of this type in the world.

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[47] https://www.nature.com/articles/s41467-017-00234-y

[48] https://www.mdpi.com/2075-163X/10/1/68

[49] https://pubs.geoscienceworld.org/gsa/geosphere/article/13/4/1066/350213/Geology-and-evolution-of-the-McDermitt-caldera

Photograph by Jorge Crespo Mena.

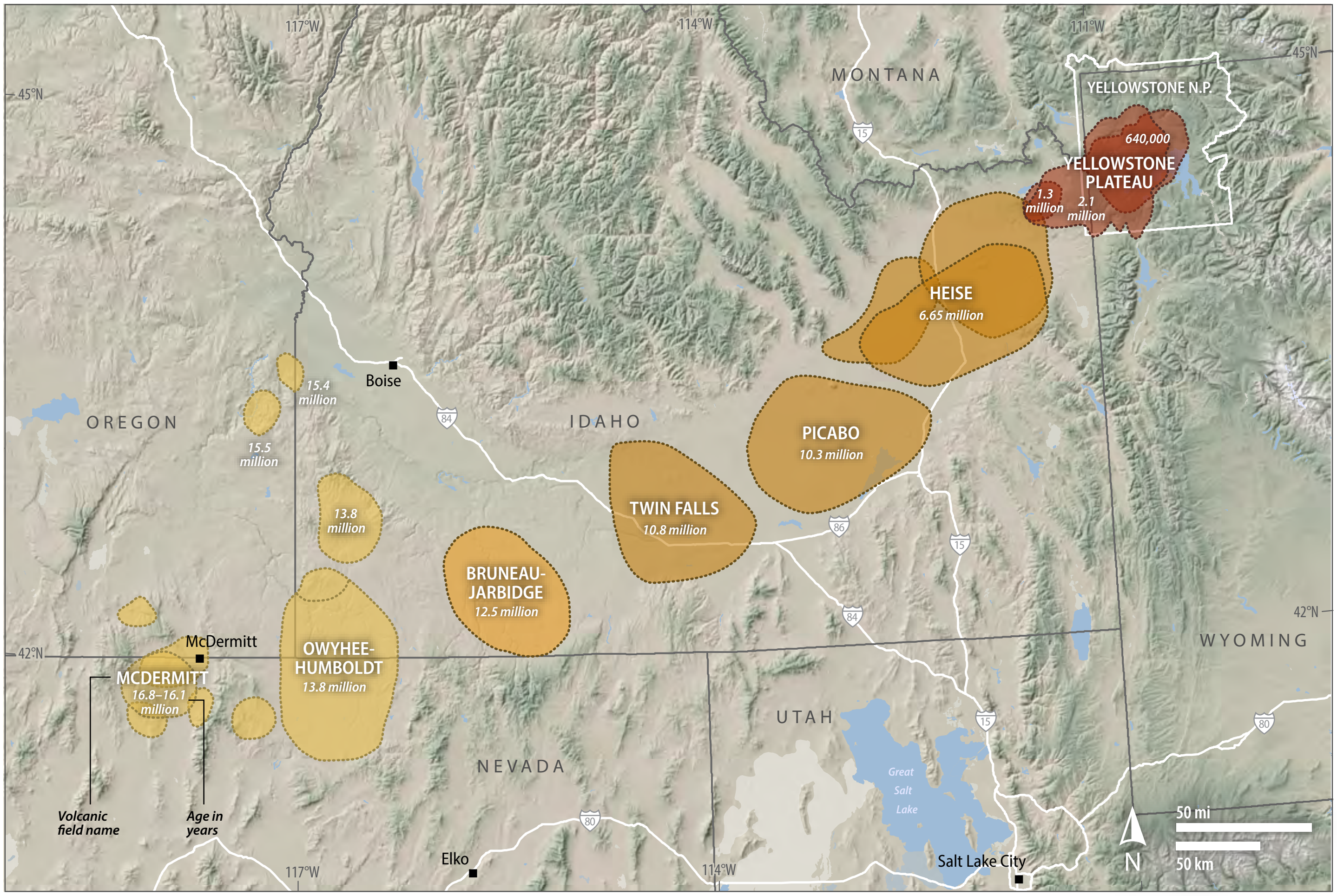

Figure 37. Caldera development in northern Nevada, southern Oregon, Idaho, and northwestern Wyoming, indicating the links between the older calderas (including McDermitt) and the present-day location of the Yellowstone hotspot. The McDermitt caldera erupted about 16.4 million years ago as an early part of the Yellowstone hotspot. Volcanism migrated to the northeast because the North American plate has been moving west-southwest over a "hotspot", a heat and magma source deep in the mantle. The calderas–supervolcanoes–of Yellowstone National Park are the modern expressions of this hotspot volcanism.

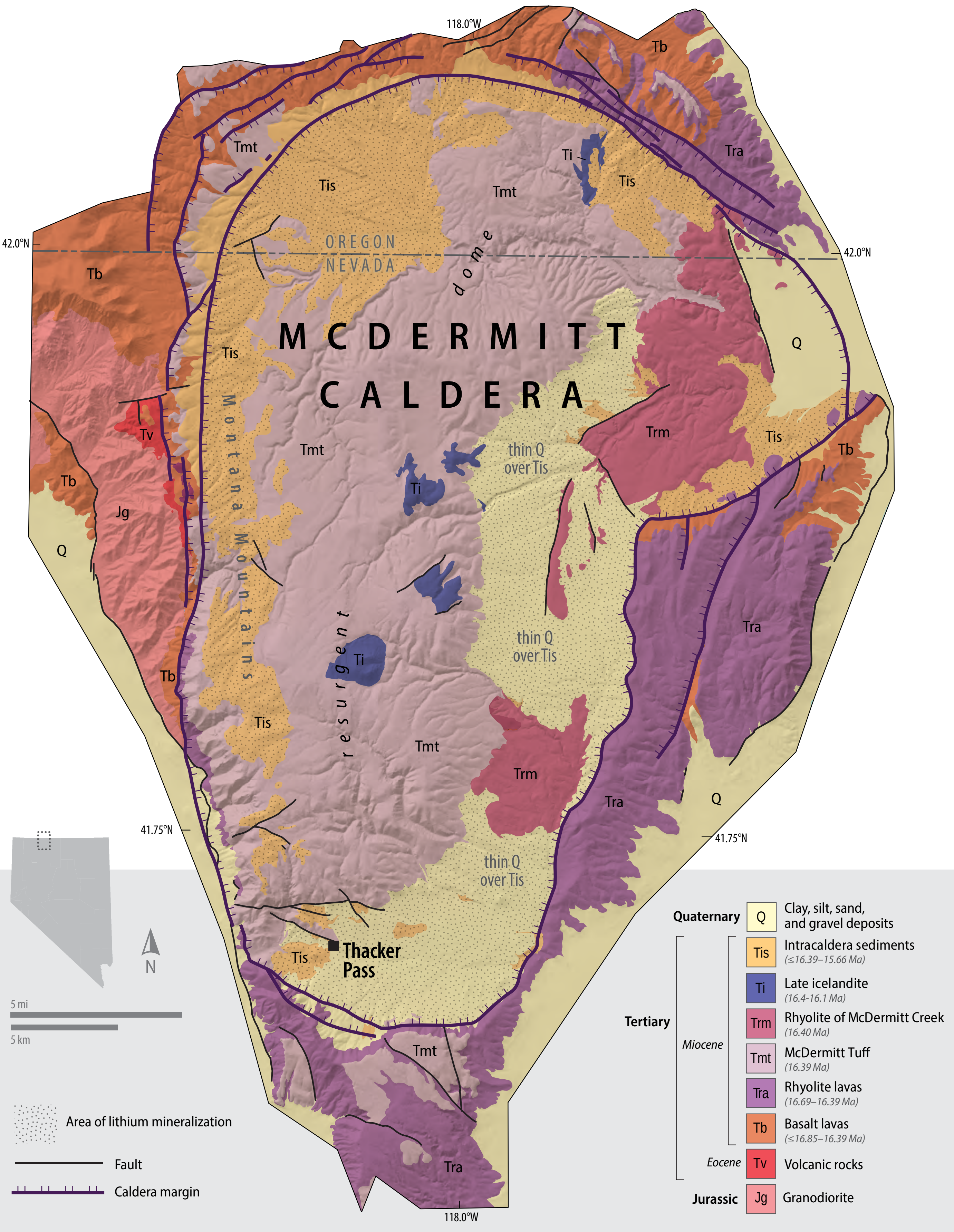

Figure 38. Simplified geologic map of the McDermitt caldera by Nevada Bureau of Mines and Geology geologists[50]. The caldera is the somewhat keyhole-shaped area bounded by caldera-margin faults. Eruption of about 1,000 km³ of magma caused collapse of the caldera along these faults. Collapse generated a large, closed hydrologic basin that was occupied by a lake, which was filled with rhyolitic tuffaceous sediments (Tis). These sedimentary rocks contain the large lithium deposits identified to date within the caldera.

Figure 39. The Thacker Pass region of the McDermitt caldera, looking north from near the southern margin of the caldera toward McDermitt Tuff, the dark partly cliff-forming rocks in the distance. The rhyolitic tuffaceous rocks that contain the Thacker Pass lithium deposit underlie the sage-brush landscape in the foreground. The tuffaceous rocks are so soft that they weather to dirt and are difficult to see without excavation (figure 40). (G. Chapel/stock.adobe.com)

The geologic evolution of the McDermitt caldera is similar to the process for general caldera formation. The area that became the caldera was preceded by abundant rhyolite and basalt volcanism, which produced a thick pile of lavas and tuffs that covered the area (figure 38[50,51,52]), as determined by mapping and ongoing research on the caldera by geologists of the Nevada Bureau of Mines and Geology[52]. The explosive eruption of the McDermitt Tuff 16.4 million years ago caused the collapse of the McDermitt caldera, the flowing of some McDermitt Tuff away from the caldera, and the accumulation of most of the tuff within the closed caldera basin[50]. Resurgence of the caldera caused the uplifting of the intracaldera (the tuff within the caldera) McDermitt Tuff into a dome, where the tuff is now exposed (figure 38). Without the resurgence, the tuff would be buried to a considerable depth, meaning that the associated lithium deposits may not have been accessible. A lake formed within the caldera almost immediately after eruption and caldera collapse, and rhyolitic tuffaceous sediments accumulated in the lake until about 15.7 million years ago. The fact that the McDermitt caldera is relatively undisturbed in terms of tectonic and geological activity after the caldera formed means that the caldera is clearly visible on satellite images and on the ground (figure 39).

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[50] https://pubs.nbmg.unr.edu/Prel-geol-McDermitt-caldera-p/of2016-01.htm

[51] https://pubs.geoscienceworld.org/gsa/gsabulletin/article/129/9-10/1027/207639/Geology-and-40Ar-39Ar-geochronology-of-the-middle

[52] https://pubs.geoscienceworld.org/gsa/geosphere/article/9/4/951/132695/Magmatism-ash-flow-tuffs-and-calderas-of-the

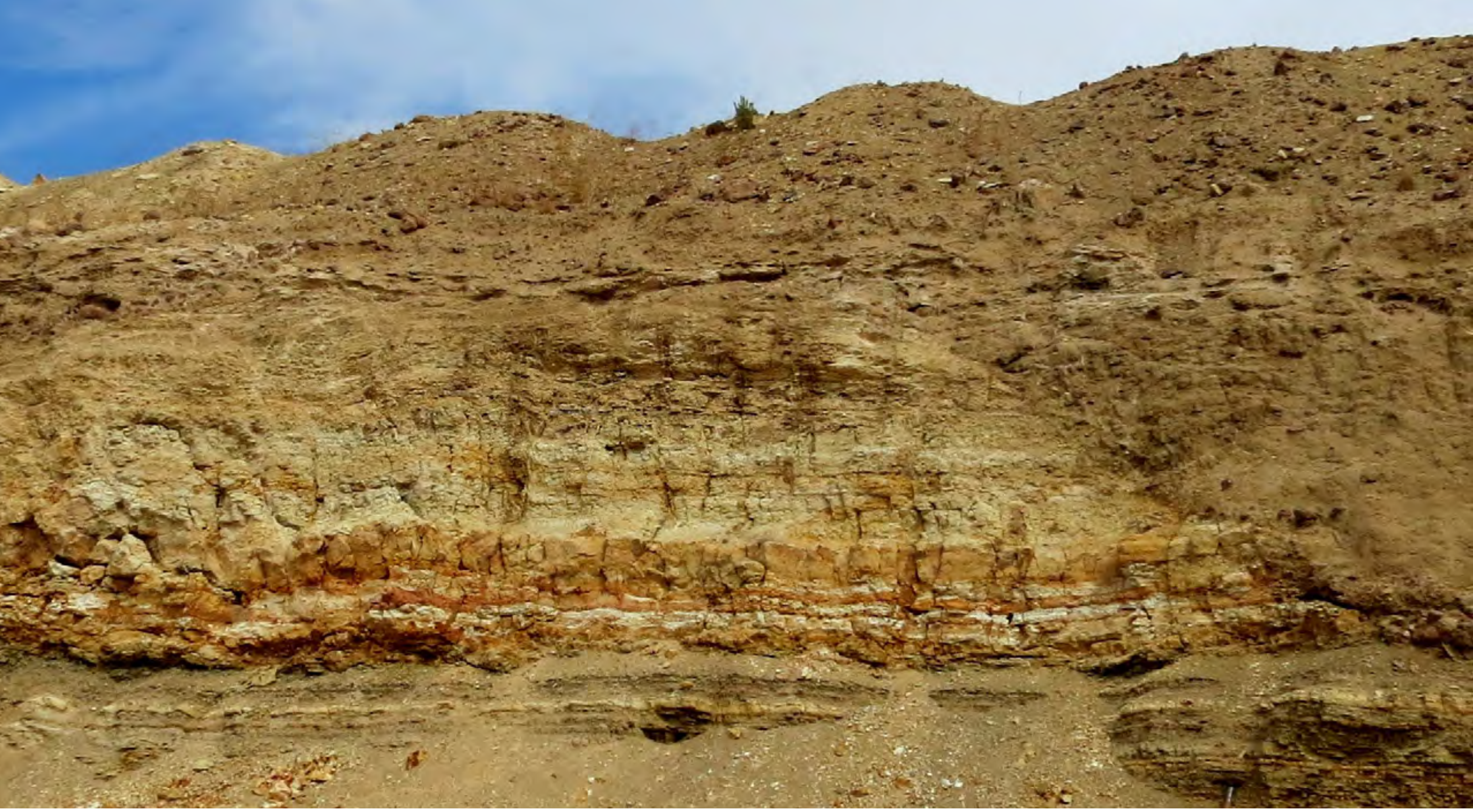

Figure 40. Lithium-bearing sediments of the McDermitt caldera. The soft, lithium-bearing rhyolitic tuffaceous rocks are exposed in an approximately 10-foot-high (3 m) exploration pit. The material at the top is a mix of dirt weathered from the tuffaceous rocks and wind-blown dust. Photograph by Christopher D. Henry.

These volcanic processes combined to generate the lithium-rich clay deposits in the caldera. However, the geologists studying the deposits do not completely agree on their origin, and the deposits and the caldera in general require further research, especially since identifying the processes involved in mineral deposit formation is crucial for the exploration for additional, similar deposits elsewhere. What is generally agreed is that the rhyolitic tuffaceous ash and associated sediments were altered, and lithium was dissolved by groundwater. Dissolution of ash and minerals within the ash greatly increased the total dissolved solids of the groundwater and led to development of new minerals to replace the ash. Because the caldera basin was closed, water could only leave the basin by evaporation, which further increased the total dissolved solids of the water, forming fluids similar to the brines described earlier. One of the minerals formed in this process is a clay called “smectite”. In the case of the McDermitt caldera, the smectite is highly enriched in lithium to concentrations as high as 4,000 ppm. Rocks composed mostly of lithium-rich smectite within the altered rhyolitic ash-sediments commonly contain 3,000 ppm lithium and occur throughout the caldera (figures 38, 40, and 41) representing potential targets for mineral exploration. However, the lithium deposits in the caldera also contain another lithium-rich clay called “illite” that has only been found in the southern part of the caldera at Thacker Pass (figures 38, 39, and 41). This lithium-rich illite contains even higher concentrations of lithium than the smectite, up to 18,000 ppm lithium, with rocks composed mostly of this lithium-rich illite commonly containing as much as 9,000 ppm lithium. Ongoing geological research is aiming to determine whether this lithium-rich illite resulted from the same type of chemical modification that produced the lithium-rich smectite more commonly found in the caldera or whether the formation of this illite involved hot hydrothermal fluids related to the magmatism in the caldera.

Figure 41. Lithium-bearing clay mineralization from Thacker Pass, showing Lithium Americas drillcore containing illite-dominated lithium clays. These rocks contain approximately 8,000 ppm lithium, which is high-grade ore. Photograph by Christopher D. Henry.

Several private companies are currently exploring the caldera and its lithium-rich smectite and illite deposits, which represent potential sources of lithium for the expanding U.S. lithium-ion battery sector. The illite deposits at this time are potentially more favorable for lithium extraction because of their higher lithium concentrations and the potential difficulty of processing smectite, which can expand when wet and may cause problems with processing. At the time of this report, Lithium Americas Corporation had started construction of a mine at Thacker Pass with full capacity lithium production commencing around 2028.

Nevada also has numerous other calderas that are geologically similar to the McDermitt caldera, including several related to the Yellowstone hotspot (figures 28 and 37). Many of these calderas had lakes within which rhyolitic tuffaceous sediments accumulated, suggesting that they may have lithium exploration potential. However, no other calderas within the Great Basin, including the other Yellowstone hotspot calderas, have any identified significant lithium mineralization to date despite considerable exploration. These calderas would seem to have all the factors contributing to lithium mineralization, namely a source of lithium in the form of rhyolitic tuffaceous sediments, transport processes by surface and groundwater within the caldera lake, and a trapping environment in a closed lake basin. Why these other calderas lack lithium mineralization is a puzzle that geologists are actively trying to answer through ongoing research within this region. One possible explanation could be that the rhyolites at the McDermitt caldera were more enriched in lithium than typical rhyolites[53,54]. Not all rhyolite magmas associated with the Yellowstone hotspot have the same lithium concentrations, which are largely derived from the generation of rhyolites by the melting of crustal rocks. This melting was driven by interaction with basaltic magma that rose from the hotspot.

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[53] https://www.nature.com/articles/s41467-017-00234-y

[54] https://pubs.geoscienceworld.org/segweb/economicgeology/article/108/7/1691/128537/Silicate-Melt-Inclusion-Evidence-for-Extreme-Pre

Figure 42. Typical environment in the Rhyolite Ridge area, with lithium-bearing sedimentary rocks in foreground. Photograph by Michael H. Darin.

Rhyolite Ridge Lithium Clay Resources

The Rhyolite Ridge area is located within the northern Silver Peak Range adjacent to Clayton Valley. This area contains significant lithium and boron resources (table 1) hosted by lake sediments of the Cave Spring Formation, which was deposited between 6 and 3 million years ago[55] (figures 42 and 43). Here, anomalously high lithium concentrations (up to 2,620 ppm lithium in rock samples) are hosted by marl (an unconsolidated sedimentary rock or soil consisting of clay and calcite), smectite and mixed illite-smectite clays, with the associated boron within the Rhyolite Ridge deposit primarily in the mineral searlesite. The Rhyolite Ridge project is operated by Ioneer USA Corp. and is, at the time of writing, in an advanced exploration and permitting phase, with resources and reserves provided in table 1. Mine construction and development are planned for later in 2024.

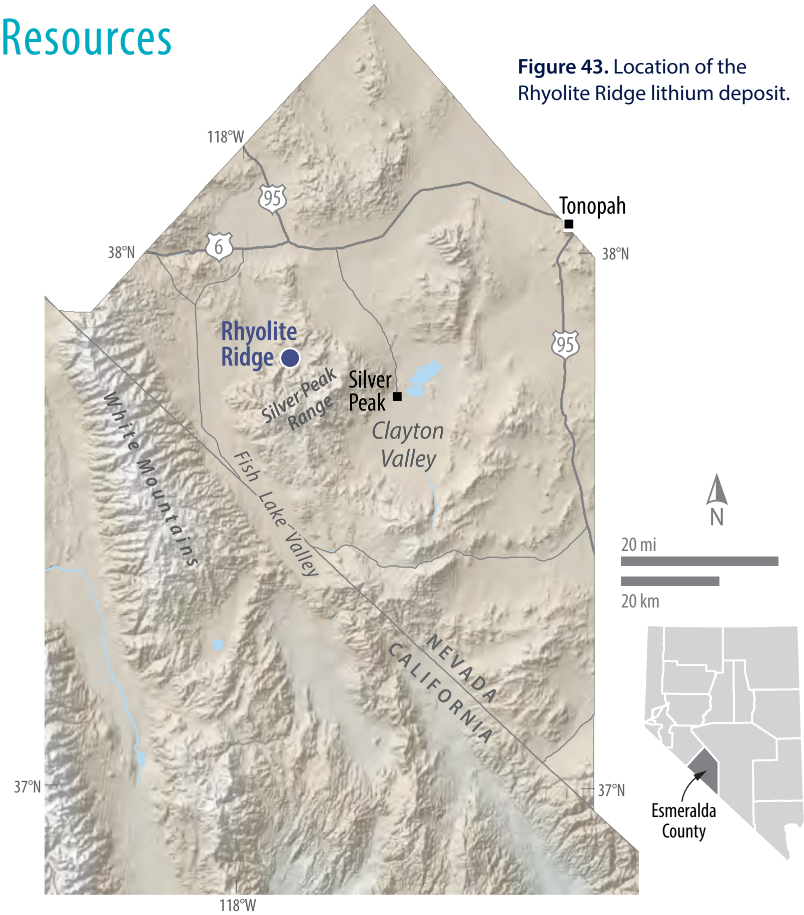

Figure 43. Location of the Rhyolite Ridge lithium deposit.

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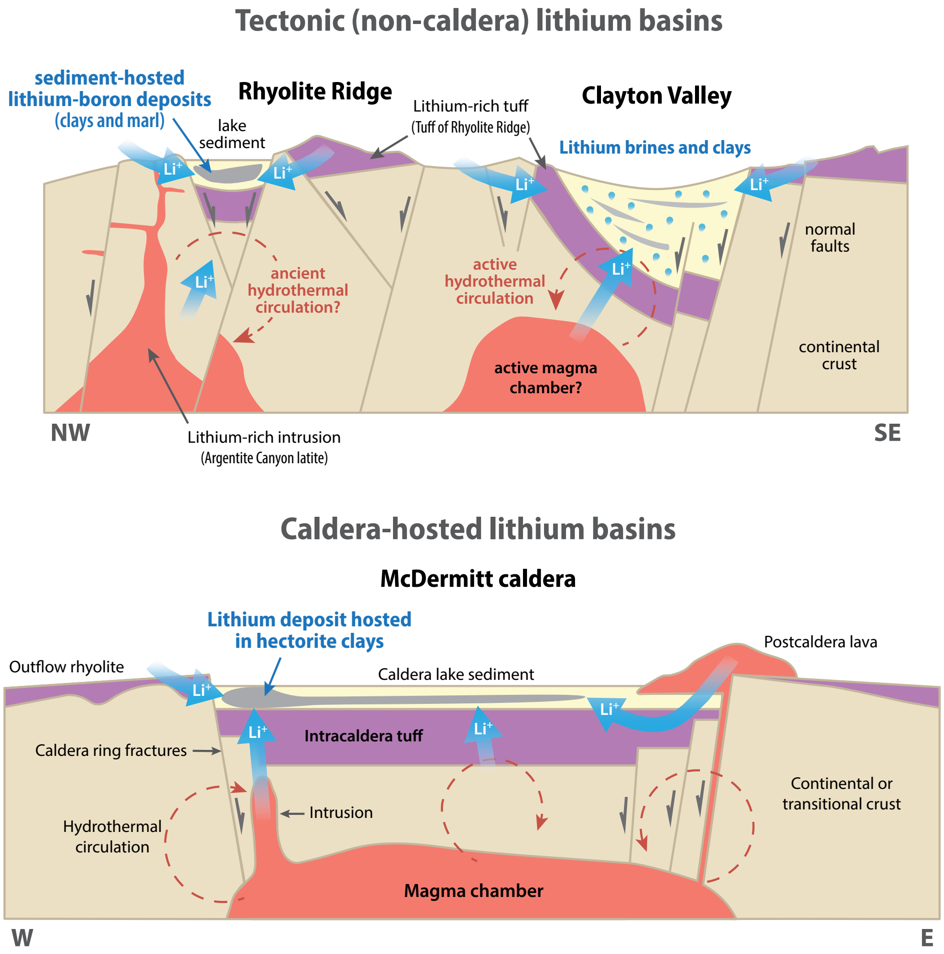
[55] Reynolds, J.T., and Chafetz, D.A., 2020, Geology of the lithium-boron Rhyolite Ridge project, Silver Peak Range, Esmeralda County, Nevada: Geological Society of Nevada Symposium, Reno, NV, p. 435–451.

Early research in this area suggested that the Rhyolite Ridge region contained a concealed or buried caldera close to these deposits[56,57], but more recent field-based research and detailed geological mapping by geologists with Ioneer and the Nevada Bureau of Mines and Geology indicate that this is not the case[58]. Instead, the lithium- and boron-enriched lake sediments were deposited in a structural basin during active extension accommodated by high-angle normal faulting, as is typical of many parts of the Basin and Range Province as mentioned earlier. This extensional basin was likely hydrologically closed, allowing for the evaporative concentration of lithium-rich fluids (or brines) and the lithium and boron enrichment of the lake sediments.

The rhyolitic volcanic rocks that are located directly beneath the lake sediments in the Rhyolite Ridge area are the probable source of lithium within the Rhyolite Ridge deposit and likely in other lithium mineralization within this region (figure 44). These rocks include the approximately 6-million-year-old tuff of Rhyolite Ridge and a series of local lavas and tuffs of the 5.9- to 5.8-million-year-old Argentite Canyon formation. Compared with typical rhyolites, these rocks have


Tectonic (non-caldera) lithium basins

Caldera-hosted lithium basins

Figure 44. Diagram comparing the environments of formation of lithium mineralization in tectonic basins, such as at Rhyolite Ridge, and caldera-associated basins, such as Thacker Pass.

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[56] https://pubs.geoscienceworld.org/gsa/gsabulletin/article/83/6/1693/7566/Petrology-of-the-Potassic-Silver-Peak-Volcanic

[57] https://pubs.nbmg.unr.edu/Geol-mineral-Esmeralda-Co-p/b078.htm

[58] https://pubs.nbmg.unr.edu/Geol-Rhyolite-Ridge-p/of2023-11.htm

Figure 45. Lithium-rich sedimentary rocks at Rhyolite Ridge. Photograph by Michael H. Darin.

Figure 46. White lithium-bearing rocks at Rhyolite Ridge in the right background with potential lithium source rocks (pink/peach colored Rhyolite Ridge tuff) in the foreground. Photograph by Michael H. Darin.

relatively high whole-rock lithium concentrations (up to 352 ppm), with more altered rocks surrounding the lithium-enriched lake sediments depleted in lithium. This suggests that lithium was removed from these altered volcanic rocks, providing the source of lithium for the deposit recipe explained earlier (p. 29). This lithium was then transported into the closed-lake basin by either meteoric (rainwater-derived) and/or hot hydrothermal fluids before interacting with and enriching the lake sediments in lithium (figure 45). Although the genesis of the lithium mineralization at Rhyolite Ridge shares the same key components as caldera-hosted lithium systems such as Thacker Pass and other lithium mineralization within the McDermitt caldera (source, transport, and concentration in a closed basin), the structural setting at Rhyolite Ridge is different from that of a volcanic caldera in that it is located in an extensional tectonic basin. This indicates that other extensional basins similar to Rhyolite Ridge and common in the Great Basin should be considered prospective for lithium exploration.

The tuff of Rhyolite Ridge has also been identified and correlated across a wider region from the northeastern White Mountains and northern Fish Lake Valley, across the Silver Peak Range and Clayton Valley, and into the Montezuma Range[59,60]. This widespread lithium-rich rhyolite tuff unit therefore may not only be the source of the clay/sediment-hosted lithium deposits at Rhyolite Ridge but also the prolific lithium brine system within Clayton Valley described earlier and for other clay/sediment-hosted lithium deposits around Clayton Valley and this broader region. However, this and some other aspects of the local and regional lithium mineralizing system at Rhyolite Ridge and the greater Clayton Valley region remain poorly understood. For instance, the spatial extent of the tuff of Rhyolite Ridge remains unknown and requires additional research to identify and correlate this unit in other areas and to document the distribution of this potential lithium source rock within the broader region. Other lithium-rich rhyolites are present in the greater Clayton Valley region and are known to have been leached of lithium by weathering and crystallization of rhyolite ash from originally glassy material like obsidian. The transporting processes that moved lithium into the Rhyolite Ridge deposit also remain unclear given that meteoric/rain-derived and hydrothermal fluids may have both been important in the transportation and deposition of lithium into the basin that hosts the Rhyolite Ridge deposit.

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[59] Ogilvie, I.A., 2023, Structure, stratigraphy, and source of sediment-hosted lithium deposits at Rhyolite Ridge, Silver Peak Range, western Nevada: University of Nevada, Reno, M.S. thesis, 153 p.

[60] Darin, M.H., Ogilvie, I.A., Harlaux, M., Reynolds, J.T., and Chafetz, D.A., in review, Structural evolution and rhyolitic source of sediment-hosted lithium-boron deposits at Rhyolite Ridge, southwestern Nevada: in review at Economic Geology.

Other Potential Lithium Resources in Nevada

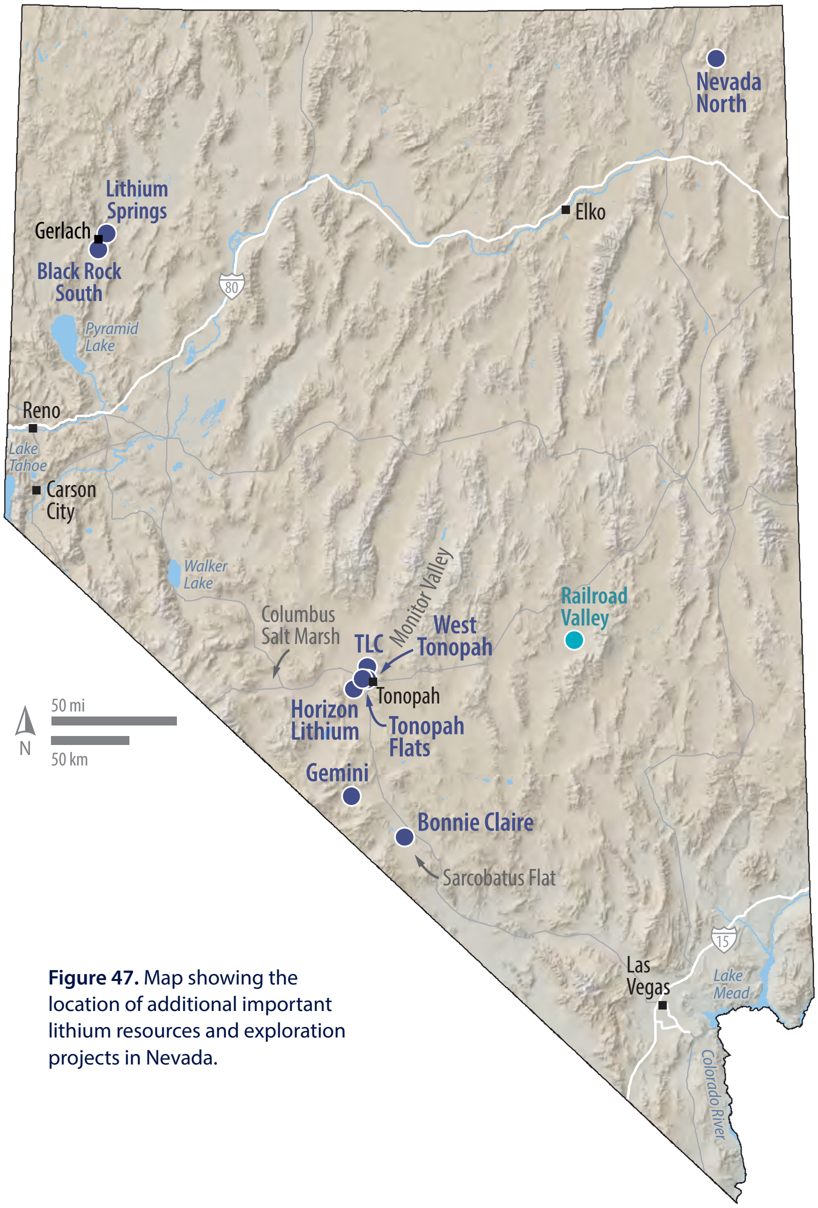

Figure 47. Map showing the location of additional important lithium resources and exploration projects in Nevada.

Numerous other lithium prospects are known within Nevada (figures 14 and 47), mostly in present-day, structurally closed basins and in now variably dissected older structurally closed basins ranging from approximately 20 to a few million years old. The increased knowledge of lithium-mineralizing systems in Nevada is also leading to the identification of other areas prospective for lithium exploration. The present-day basins that are currently the focus are geologically similar to Clayton Valley and have been explored for both lithium-clay deposits and lithium brines. Basins with known exploration and reported lithium concentrations include Columbus Salt Marsh, Monitor Valley (clay deposits), Sarcobatus Flat (Bonnie Claire), and more, with some of the identified deposits with reported resources listed in table 1.

Figure 48. Location of the Bonnie Claire playa, containing significant lithium resources. (davidrh/stock.adobe.com)

Figure 49. Close-up image showing dessication (drying out) cracks within the Bonnie Claire playa crust. (davidrh/stock.adobe.com)

One area just west of Tonopah with considerable recent exploration is an example of lithium mineralization contained in an older structural basin, but one that has not been significantly tectonically dissected since it formed. Several companies have identified lithium smectite-hosting clay/sedimentary deposits in the Siebert Tuff, a series of Miocene sediments that accumulated within the older structural basin in this region. At least some of the rhyolitic ash within the Siebert Tuff was derived from contemporaneous volcanic activity in and around Tonopah[61]. Reported lithium concentrations range from 1,000 to 2,000 ppm, and surface water drainage is into the Big Smoky Valley and to a playa in the lowest part of the valley to the south of Highway 95 about 25 miles (40 km) west of Tonopah. The Big Smoky playa and surface drainage area are parts of the probable groundwater basin that feeds into Clayton Valley and are also being actively explored for lithium (figure 32). Whether other similar mineralization exists elsewhere in the state remains unclear but is certainly an area for further research and exploration.

Research by scientists and engineers within the Nevada System of Higher Education is helping Nevada become a leader in all aspects of the lithium economy. Geologists are investigating how the lithium deposits formed and the nature of the associated mineralizing systems and mineralization, enabling the identification of highly prospective areas for lithium exploration and mining, and generating data vital for the extraction of lithium from these systems. Metallurgical and mineral processing engineers are discovering approaches to optimizing extraction of lithium from clay deposits and brines. Biologists are studying approaches to preserving endangered plants and animals that occur near deposits, and hydrogeologists are understanding the importance of water on the formation of lithium mineralization as well as how to conserve water during lithium extraction.

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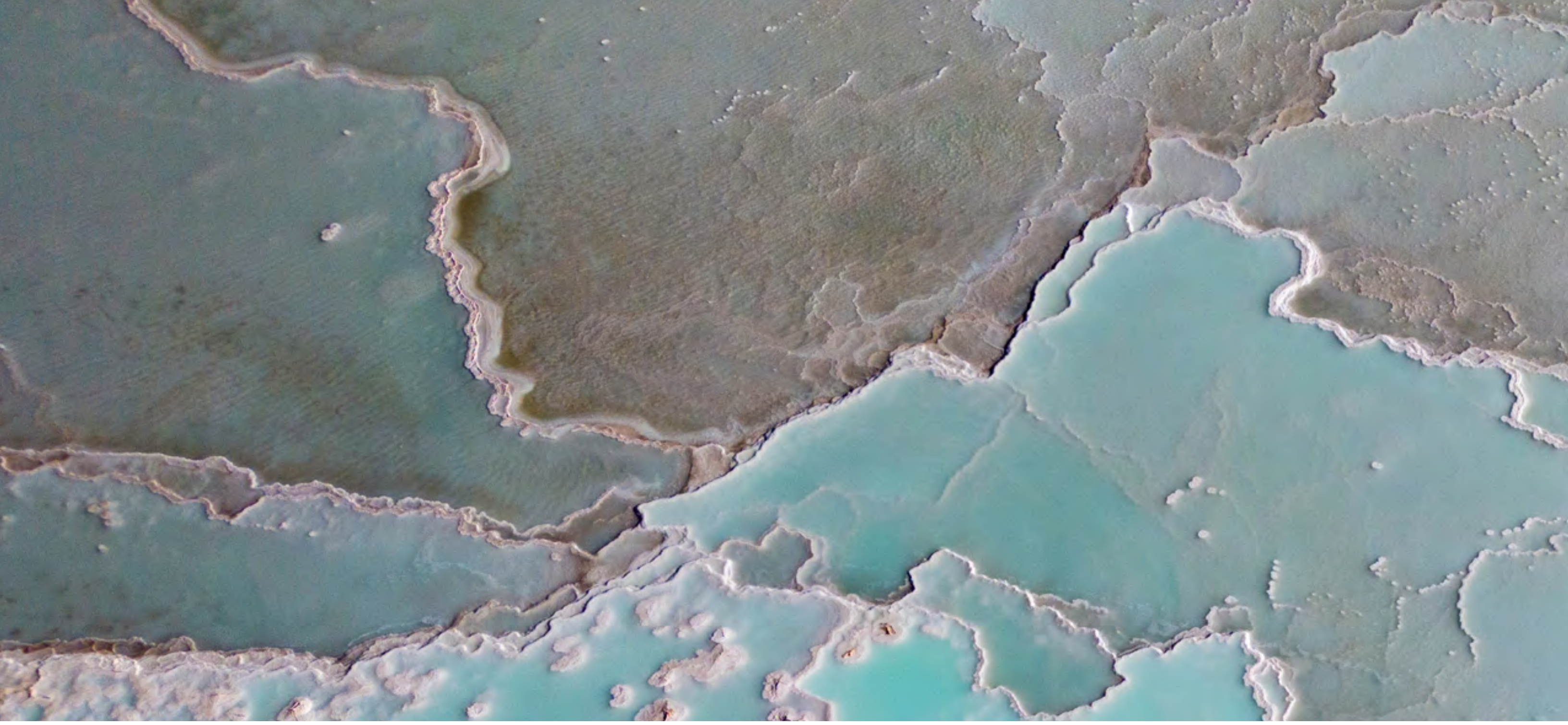
[61] https://pubs.nbmg.unr.edu/Geology-of-the-Tonopah-Lone-Mtn-p/b092.htm



(freedom_wanted/stock.adobe.com)

Conclusions

Nevada is unique in the U.S. in that it contains all aspects of the lithium supply chain, including large mineral deposits formed by numerous geological processes. This means that Nevada is ideally suited to supply the lithium required not only by lithium-ion battery manufacturing within the state but also potentially elsewhere in the U.S., representing a potentially secure domestic source of the raw material required for the lithium economy. This is crucial given the significant increase in demand for lithium as a result of expansions in the U.S. lithium-ion battery industry. Other potential sources of lithium exist within the U.S., such as lithium pegmatites (Plumbago in Maine, Kings Mountain in North Carolina) and oilfield brines from the Smackover Formation in Arkansas, Texas, Alabama and elsewhere in the southern U.S. However, pegmatite occurrences are rare compared to the significant reserves and resources of lithium-rich sedimentary or clay deposits in Nevada. Equally, legislation in some states such as Maine is likely to inhibit the development of lithium mines there, further restricting the likelihood of development of these resources compared to those in Nevada. The extraction of lithium from oilfield brines and other unconventional sources requires further development of technologies; such as Direct Lithium Extraction; that still remain unproven. The advent of these new technologies and the enhanced extraction potential of alternative sources such as geothermal waters and oilfield brines may also require policy development to address current uncertainties in permitting, leasing, and project development. Finally, the capacity of these resources outside of Nevada to meet the annual lithium demand outlined in the introduction to this report remains uncertain, especially with competition in the geothermal sector from energy generation requirements. All of this means that secure, domestic sources of lithium are most likely to be derived from the already known and characterized deposits in Nevada (table 1), especially given that Nevada currently has the largest lithium reserves and resources of any U.S. state. The potential for discovery of more lithium mineralization in Nevada is also growing, as research and exploration enables us to better understand the processes that form lithium sources, transport lithium, and facilitate the formation of lithium deposits.

By harnessing the power of geothermal energy while harvesting lithium-rich brines, Nevada can play a pivotal role in driving the transition toward a more sustainable, electrified future. As a source of renewable energy, geothermal power also represents just one of several opportunities that highlight Nevada's current and potential contribution to the energy transition and the move away from fossil fuels to low- and zero-carbon-dioxide energy generation, storage, and transport. Lithium is certainly also needed for the electric vehicles that reduce the need for fossil fuels in transportation. Not only does Nevada have abundant lithium resources but also has facilities that represent the entire lithium supply chain, from mining to battery production and eventual recycling, indicating just one way that Nevada is capitalizing on abundant renewable energy opportunities. With hydroelectric power produced at Hoover Dam, wind farms in several portions of the state, and solar farms taking advantage of approximately 300 days of sunshine each year, Nevada is rapidly expanding its renewable energy production and attracting other businesses that have significant demands for electricity and battery storage.

In summary, the economic security of the U.S. and Nevada lithium-ion battery industries as well as associated economic sectors will require significant development of lithium supply and refining capacity. This is also vital for future developments given the current rapid expansion of U.S. battery manufacturing capacity. The information outlined in this report strongly suggests that the growing U.S. lithium-ion battery sector is best served by the development of secure domestic lithium supply chains from plentiful mineral resources within Nevada.

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