CRITICAL MINERALS OF UTAH

Second Edition

by Stephanie E. Mills and Andrew Rupke

CIRCULAR 135
UTAH GEOLOGICAL SURVEY
UTAH DEPARTMENT OF NATURAL RESOURCES
2023

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Cover photo: *Great Salt Lake's north arm showing slushy mirabilite, a hydrous sodium sulfate mineral that forms in the winter and dissolves in the spring when temperature rises. Photograph was taken near the Spiral Jetty.*

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CRITICAL MINERALS OF UTAH - SUMMARY

Utah is a state with diverse geology and natural resources, and this diversity extends to mineral resources that are deemed critical by the U.S. Department of the Interior. Utah's critical mineral portfolio includes current producers, known resources, areas of past production, and undeveloped occurrences. This report, now in its second edition, summarizes the geographic and geologic distribution of critical minerals within Utah. Utah is notable for being the global leader in beryllium production; being the only domestic producer of magnesium metal; being one of only two states producing lithium (as of publication); and being a byproduct producer of tellurium, platinum, and palladium from the world-class Bingham Canyon mine, which is one of only two domestic tellurium producers. Utah has known resources of aluminum, fluorspar, germanium, gallium, indium, vanadium, and zinc, as well as past production and occurrences of many other critical minerals. In total, Utah currently produces 6 critical minerals, has known resources of 7 more, and hosts an additional 27 as past producers and/or occurrences with limited potential for economic development.

Highlights of Utah's critical minerals include:

- Global leader of beryllium: The Spor Mountain district in central Juab County is the largest global beryllium producer, and the yet-to-be-mined bertrandite ore still contained in the district is enough to continue mining at current rates for another 75 years.
- Only domestic source of magnesium metal production: Utah is the only domestic producer of magnesium metal from a primary source (Great Salt Lake brines).
- One of only two domestic lithium producers: Utah, along with Nevada, are the only two states to currently produce lithium, with Utah's production being a byproduct of magnesium recovery from Great Salt Lake brines. Utah also hosts additional known resources of lithium currently in development.
- Bingham Canyon byproduct tellurium, platinum, and palladium: The world-class Bingham Canyon mine, central to the most historically productive mining district in the United States, began recovering byproduct tellurium from copper refining in 2022, along with ongoing crude byproduct platinum and palladium production. Bingham Canyon is one of only two domestic tellurium producers.
- Rare indium, germanium, and gallium deposits: The West Desert zinc-copper-indium skarn deposit is the only established domestic resource of indium, and the Apex mine is one of the only known domestic resources of gallium and germanium.
- Known resources of aluminum and fluorspar: The Blawn Mountain alunite deposit, containing potential for both aluminum and potash, is the largest known alunite deposit in the country. Once online, the Lost Sheep Fluorite mine will be the only significant fluorspar producer in the country.
- Notable domestic vanadium resource: The Colorado Plateau, including southeast Utah, is the most significant vanadium-bearing region in the United States, and the White Mesa Mill in Blanding, Utah, is the only conventional mill capable of processing and refining vanadium from ore.
- Prolific historical production: Utah has historically been a major domestic producer of bismuth and has produced notable amounts of arsenic, antimony, barite, manganese, and tungsten.

INTRODUCTION AND UPDATES

Critical minerals, previously known as strategic, essential, or vital minerals or materials, refers to commodities that are necessary to a country's economic or national security but may have vulnerabilities in the supply chain, and for which there are few or no viable substitutes. The concept of critical minerals is not new, and in the United States various lists of commodities and definitions of what qualifies as critical have been developed since the early 1900s. The commodities considered critical have evolved over time, taking into consideration changes in the demand for minerals and the production landscape. For example, the list of strategic and critical materials in 1945 included asbestos, which is now considered highly toxic; beryl for beryllium, of which the United States is now the dominant global producer; and manganese and vanadium, which are still considered critical today. One of the most drastic changes in mineral demand in modern times has been driven by the spread of high-tech devices and new battery technology, both of which require a wider variety of raw materials than technology from previous decades. Changes in the global production of minerals result from geologic scarcity, evolving land use restrictions, environmental regulations, geopolitical disputes, and market dynamics. In evaluating the criticality of a mineral commodity, a number of factors are considered, such as import reliance, production concentration (i.e., most of a commodity comes from only one or two countries), governance risk, and the potential impact of supply disruption.

Critical minerals in the United States returned to prominence in recent years with a new list published in 2018 (Fortier and others, 2018), followed by a review and updated list published in 2022 (Burton, 2022). The first edition of *Critical Minerals of Utah* (Mills and Rupke, 2020) addressed the critical minerals listed in the 2018 publication. This edition of the report addresses changes and updates to the 2022 federal critical mineral list and incorporates Utah Geological Survey (UGS) scientists' work with the U.S. Geological Survey (USGS) Earth Mapping Resources Initiative (Earth MRI) program to identify nationwide focus areas of potential domestic critical mineral resources (Dicken and others, 2022). Changes to the federal critical mineral list from 2018 to 2022 include:

1. addition of nickel and zinc as critical minerals;
2. removal of helium, potash, rhenium, and strontium as critical minerals;
3. exclusion of uranium as a critical mineral because of its status as a fuel mineral; and
4. splitting elements in the Platinum Group Element (PGE) and Rare Earth Element (REE) mineral groups into individual entries (figure 1 and table 1).

The 2022 changes to the list are significant for Utah because Utah produces potash, helium, and rhenium and has significant known resources of uranium, all of which were removed from the critical mineral list. Utah also has known resources of zinc which was added to the list.

As a result of the changes, the current critical mineral list has increased from 35 to 50 and now includes aluminum, antimony, arsenic, barite, beryllium, bismuth, cerium, cesium, chromium, cobalt, dysprosium, erbium, europium, fluorspar, gadolinium, gallium, germanium, graphite, hafnium, holmium, indium, iridium, lanthanum, lithium, lutetium, magnesium, manganese, neodymium, nickel, niobium, palladium, platinum, praseodymium, rhodium, rubidium, ruthenium, samarium, scandium, tantalum, tellurium, terbium, thulium, tin, titanium, tungsten, vanadium, ytterbium, yttrium, zinc, and zirconium. The Energy Act of 2020 directs the USGS to review and update the critical mineral list every three years so a new federal critical mineral list is expected in 2025.

Utah has abundant and diverse mineral commodities, including many of those currently identified as critical. As one of the top 10 states for mineral production value for the past decade, Utah is prospective for the development of domestic critical mineral resources. Utah also hosts four distinct geologic domains: the Basin and Range Province, the Transition Zone, the Colorado Plateau, and the Middle Rocky Mountains, all of which have their own unique geologic history and metallogenic evolution, making Utah one of the most diverse states for exploration potential (figure 2). This publication offers an overview of Utah's critical mineral production and resources.

This report is divided into sections based on the degree of resource development: current production, known resources, past production (limited potential), mineral occurrences, and minerals with no known potential for development in Utah. The degree of resource development is based on the status of projects as of the end of 2022, and projects may have progressed or been deprioritized since.

- Current production includes operations that are actively mining critical minerals or producing critical minerals as a byproduct of mining other commodities. Byproduct producers take steps to refine a critical mineral, though may not produce it in final form (e.g., Bingham Canyon platinum, palladium, and tellurium).
- Known resources are projects that are near to production or have published a mineral resource report based on modern exploration methods and data, giving a high degree of confidence in the estimate.
- Past production includes critical minerals that have been historically produced in Utah but have limited potential based on current economics.
- Mineral occurrences represent areas of known critical mineral enrichment but with limited study or insignificant resources.
- Critical minerals with no known potential are those that are not known to occur in Utah or have no known potential for development.

The information in this report is drawn from a variety of sources including USGS Mineral Commodity Summaries, UGS annual mining surveys and historical documents, mining company websites, press releases, technical reports, the Utah Division of Oil, Gas and Mining website, and communication with industry geologists. References to mining districts in the text and in maps are based on the modern definitions established in Krahulec (2018). Throughout this report, maps of Utah that show Great Salt Lake use the extent of the lake at the 4190 ft level, which is roughly accurate for winter 2022. Suggestions for further reading are included at the end of the sections for individual critical minerals.

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***Figure 1. (A)** Periodic table showing changes between the 2018 and 2022 federal critical minerals identified by the U.S. Geological Survey, and **(B)** periodic table highlighting critical minerals found in Utah, highlighted according to their current resource status.*

Table 1. Summary of U.S. critical minerals and their presence in Utah.

Commodity	Symbol	Top Global Producer[1]	U.S. Import Reliance[1] (%)	Notable Utah Locations
Critical Minerals Produced in Utah				
Beryllium	Be	United States (Utah)	16	Juab Co.
Lithium	Li	Australia	>25	Great Salt Lake, Grand and San Juan Cos. (Paradox Basin)
Magnesium metal	Mg	China	<50	Great Salt Lake
Platinum and Palladium	Pt, Pd	South Africa	70, 37	Salt Lake Co. (Bingham mine)
Tellurium	Te	China	>95	Salt Lake Co. (Bingham mine)
Known Critical Mineral Resources in Utah				
Aluminum	Al	Australia (bauxite)	>75 (bauxite)	Beaver Co.
Fluorspar	F (CaF_2)	China	100	Juab Co.
Germanium and Gallium	Ge, Ga	China	>50, 100	Washington Co.
Indium	In	China	100	Juab Co.
Vanadium	V	China	100	San Juan, Grand, and Emery Cos.
Zinc	Zn	China	76 (refined)	Juab and Utah Cos.
Past Production (Limited Potential) of Critical Mineral Resources in Utah				
Antimony	Sb	China	84	Garfield, Salt Lake, and Box Elder Cos.
Arsenic	As	Peru	100	Tooele Co.
Barite	Ba ($BaSO_4$)	China	>75	Juab and Tooele Cos.
Bismuth	Bi	China	90	Salt Lake, Juab, and Tooele Cos.
Manganese	Mn	South Africa	100	Juab, Millard, Emery, Grand, San Juan, Tooele, Beaver, Piute, Utah, and Salt Lake Cos.
Tungsten	W	China	>50	Tooele, Box Elder, Juab, Millard, Beaver, and Salt Lake Cos.
Critical Mineral Occurrences in Utah				
Cobalt	Co	Congo	76	
Tin	Sn	China	78	
Rare Earth Elements and Scandium	La, Ce, Pr, Nd, Pm, Sm, Eu, Gs, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y	China	>90[2]	
Titanium, Zirconium, and Hafnium	Ti, Zr, Hf	China (Ti), Australia (Zr, Hf)	90 (Ti[3]), <25 (Zr), not available (Hf)	
Critical Minerals with No Known Potential in Utah				
Cesium, Rubidium	Ce, Rb	China (?)	100	
Chromium	Cr	South Africa	80	
Graphite	C	China	100	
Nickel	Ni	Indonesia	48	
Niobium and Tantalum	Nb, Ta	Brazil, Congo	100	
Other Platinum Group Elements	Ir, Os, Rh, Ru	South Africa	not available	

[1]Source: U.S. Geological Survey Mineral Commodity Summaries (2022)
[2]The U.S. exports a minor amount of mineral concentrates for processing, but is reliant on imports of REE compounds
[3]Titanium mineral concentrates

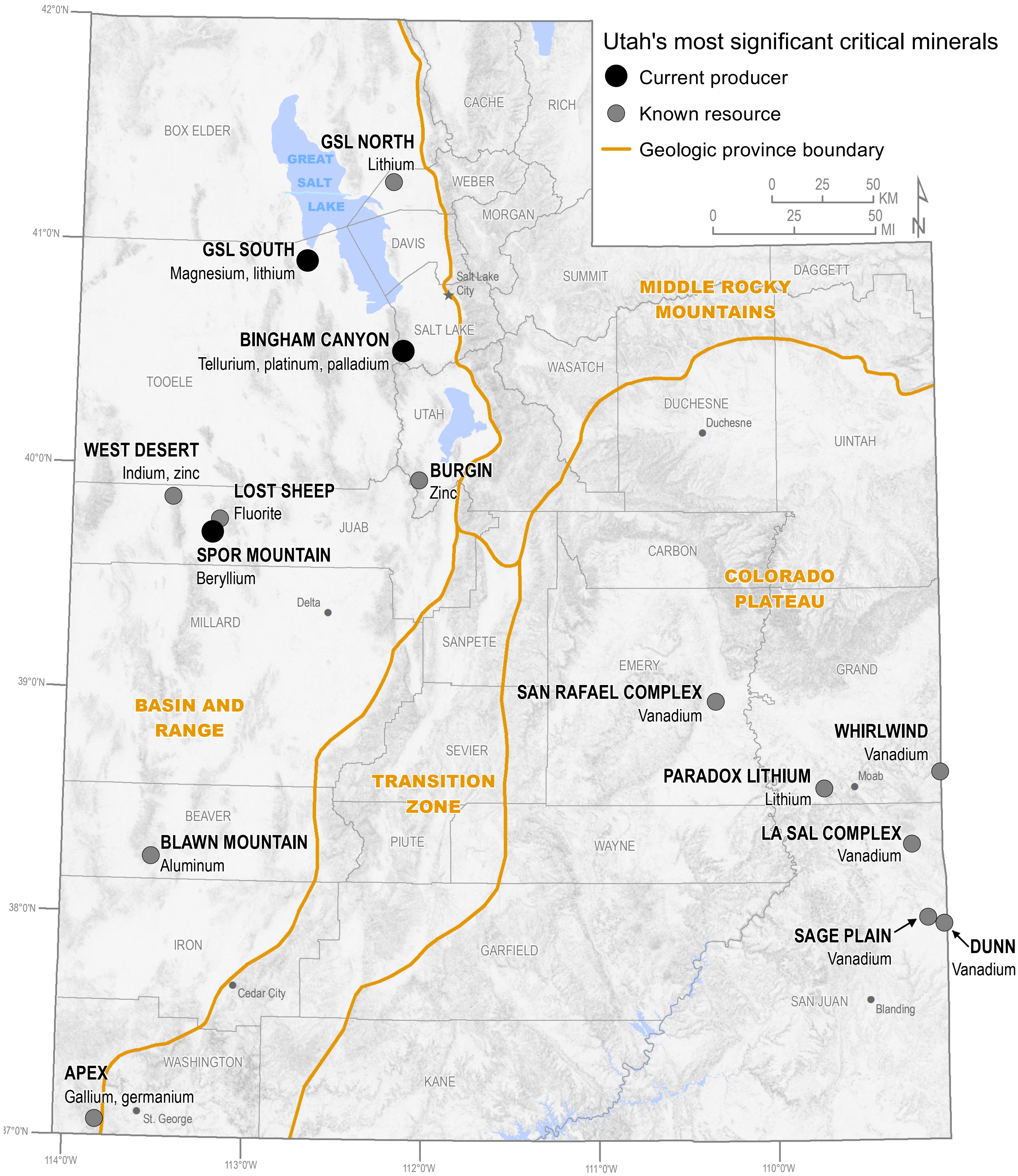

Figure 2. *Summary of the distribution of Utah's most significant critical minerals.*

CRITICAL MINERALS PRODUCED IN UTAH

Beryllium

Overview and Criticality

Beryllium is the lightest of the alkaline earth metals (the elements found in the second column of the periodic table) and the second lightest metal after lithium. Despite being 30% lighter than aluminum, beryllium has 50% greater rigidity than steel, one of the highest melting points for light metals (2349°F for beryllium, versus 1221°F for aluminum and 357°F for lithium), and is an excellent electrical and thermal conductor. These characteristics make beryllium metal a highly desirable material for many aerospace applications, where value is placed on lightweight materials that can withstand mechanical distortion and extreme temperature variation. Beryllium is also important in alloys; copper, for example, is strengthened by a factor of six when 2% beryllium is added.

Beryllium's main use in the United States is in industrial components and for aerospace and defense applications, but it is also an important component for automotive and consumer electronics, telecommunications infrastructure, and energy applications. Beryllium is particularly important to the U.S. military for its aerospace and defense applications, which include beryllium componentry in missiles, fixed-wing aircraft, helicopters, tanks, satellites, and communication hubs and applications ranging from navigation to structural components to optical systems. The primary mirror of the James Webb Space Telescope, the largest optical telescope to date in space, is composed of 18 gold-coated hexagonal beryllium mirror segments, the beryllium of which came from Utah (NASA Earth Observatory, 2021). In 2008, the U.S. Department of Defense stated that beryllium is "essential for important defense systems and unique in the function it performs." This link to defense is the basis for beryllium's criticality, along with its single-source supply chain. Unlike most minerals on the critical mineral list, which have a high import reliance, the United States is the leading global producer of beryllium. However, because 65% to 85% of global beryllium production has been traditionally sourced from the Spor Mountain district in Juab County, any compromise to the operation would have strong negative impacts on the entire beryllium supply chain.

Sources and Geology

Beryl ($Be_3Al_2Si_6O_{18}$) and bertrandite ($Be_4Si_2O_7[OH]_2$) (figure 3) are the main ore minerals for beryllium. Beryl contains 14% beryllium oxide (BeO), whereas bertrandite contains 42%; however, economic concentrations of bertrandite tend to be disseminated, such that the overall grade of bertrandite operations are lower than that of beryl mines. Bertrandite ores are amenable to acid-leaching, as opposed to the flotation and grinding often used in beryl processing, which is a significant boost to the economics of bertrandite operations. Beryl deposits are the main source for beryllium outside of the United States and are associated with pegmatites enriched in other rare metals such as lithium, cesium, and tantalum (LCT-type pegmatites).

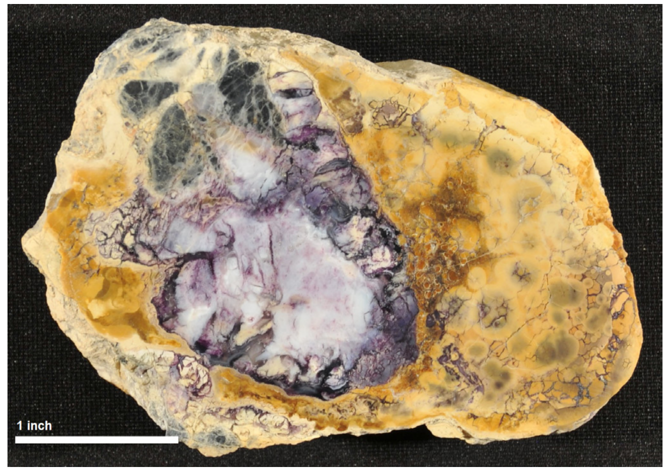

Figure 3. *Replacement-style beryllium mineralization from the Spor Mountain district. Sample courtesy of Mark Milligan.*

Economic bertrandite deposits are volcanogenic in nature, though bertrandite can occur in vein-hosted carbonate replacement deposits or with beryl in skarn deposits. The Spor Mountain mining district in Juab County is a unique volcanogenic carbonate replacement deposit. The ore horizon exists in the 25-million-year-old (Ma) Spor Mountain Formation, a pyroclastic tuff containing carbonate clasts of underlying Paleozoic sequences. The Spor Mountain Formation is overlain by a topaz-bearing rhyolite. Over millions of years (roughly 26 to 2 Ma), beryllium was leached by hydrothermal fluids from Be-enriched volcanic glass in the tuff and redeposited in the carbonate clasts, causing carbonate to be replaced by bertrandite along with fluorite, calcite, and microcrystalline/amorphous silica. The resulting purple color of these nodules is not due to the bertrandite, which itself is clear, but rather the fluorite associated with the bertrandite.

Beryllium in Utah

Utah hosts several areas with known beryllium mineralization (figure 4), but the Spor Mountain district is the only area where it is mined. Beryllium at Spor Mountain was first recognized in 1959, even though the district had previously been known for fluorspar (discovered in the 1930s by Fay Spor) and uranium (discovered in the 1950s). In the early 1960s, before the official beryllium discovery had been made, geologists recognized the potential for a world-class deposit. In fact, the possible reward was considered so great that mining companies resorted to a tactic known as claim jumping, where a company illegally takes possession of the ground under another company's mining claim. The laws at the time offered little protection to companies that were not actively working their claims, and a claim jumper who made a discovery could be rewarded with the claims and their mineral value. In the case of Spor Mountain, a larger explorer had not yet been actively drilling their claims

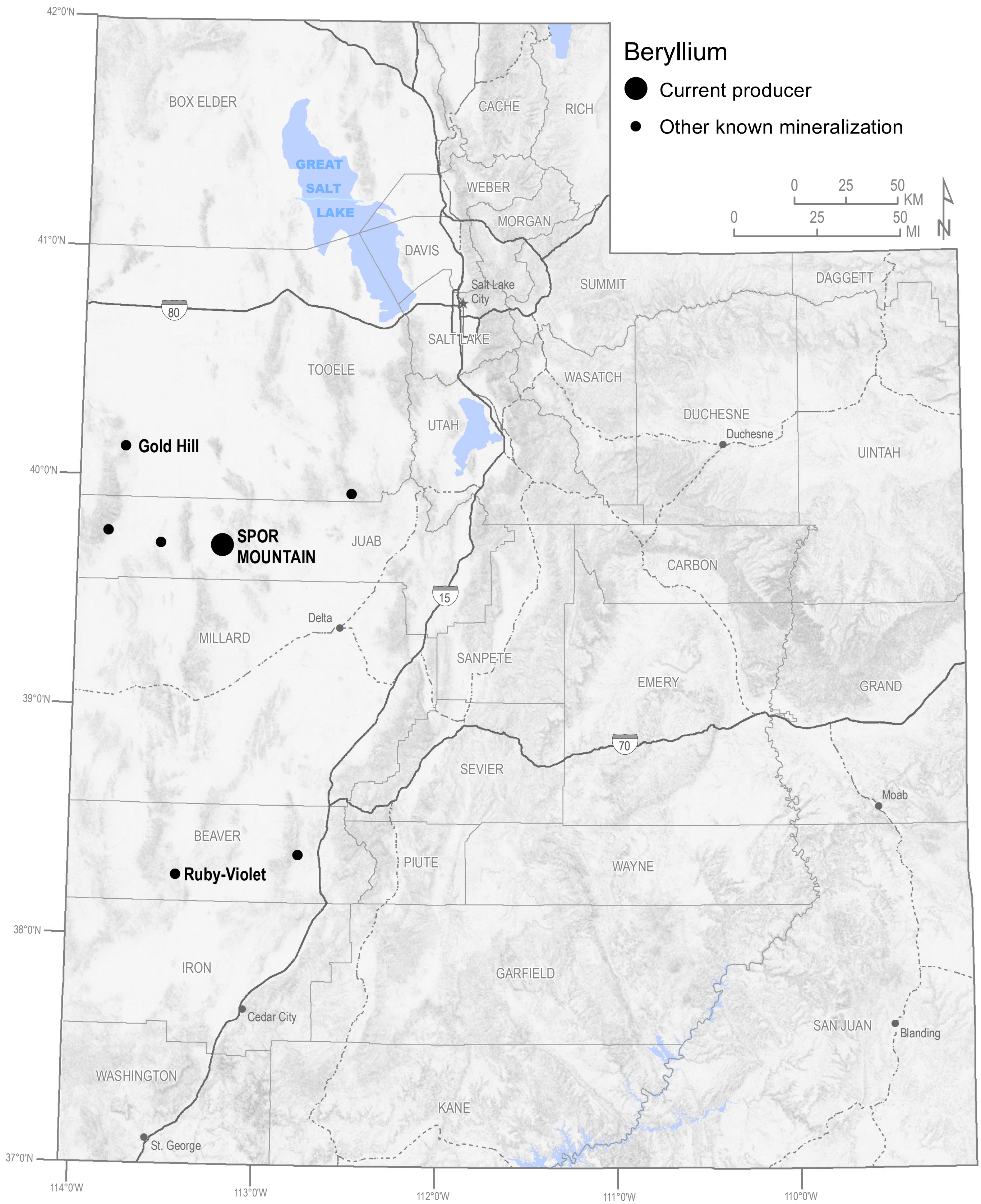

Figure 4. *Beryllium mineralization in Utah.*

and a junior explorer sought to take advantage of this lapse and make the discovery first. What followed has become known as the Mining War at Topaz Mountain. The conflict between the companies evolved into something out of a Wild West novel and included covert drilling by night, midnight meetings with judges for restraining orders, detective agencies, armed guards, nighttime four-wheel-drive pursuits, equipment sabotage by gunfire, hotwiring of drill rigs, car crashes, and one relentless lawyer who was hit with a shovel and had two ribs broken over the course of the dispute.

Despite the initial drama that formed the Spor Mountain district, the claim disputes were settled and Brush Wellman Company, now known as Materion, eventually consolidated ownership of the district. Materion has remained the operator ever since. Open-pit mining began in 1968, and a processing mill near Delta, Utah, opened in 1969. The mill was custom developed to handle the low-grade bertrandite ore and refine it to beryllium hydroxide ($Be[OH]_2$). Beryllium has been produced from the Spor Mountain district continuously for over 50 years, and Materion reports indicate nearly 10 million tons of reserves, which is estimated to last a minimum of 75 years at the current rate of mining.

Other areas with subeconomic beryllium mineralization include the Gold Hill district in Tooele County, and an area in the Wah Wah Mountains of Beaver County where red beryl is mined from the Ruby-Violet mine, the only known source of gem quality red beryl in the world.

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Utah Spotlight: Beryllium Belt

The Beryllium Belt of western Utah (figure 5) was first defined by Cohenour (1963) and has remained a generalized term for a series of beryllium occurrences stretching east-west from the West Tintic Mountains in central Utah to the southern Deep Creek Range near the border with Nevada. The Beryllium Belt, characterized by late Oligocene

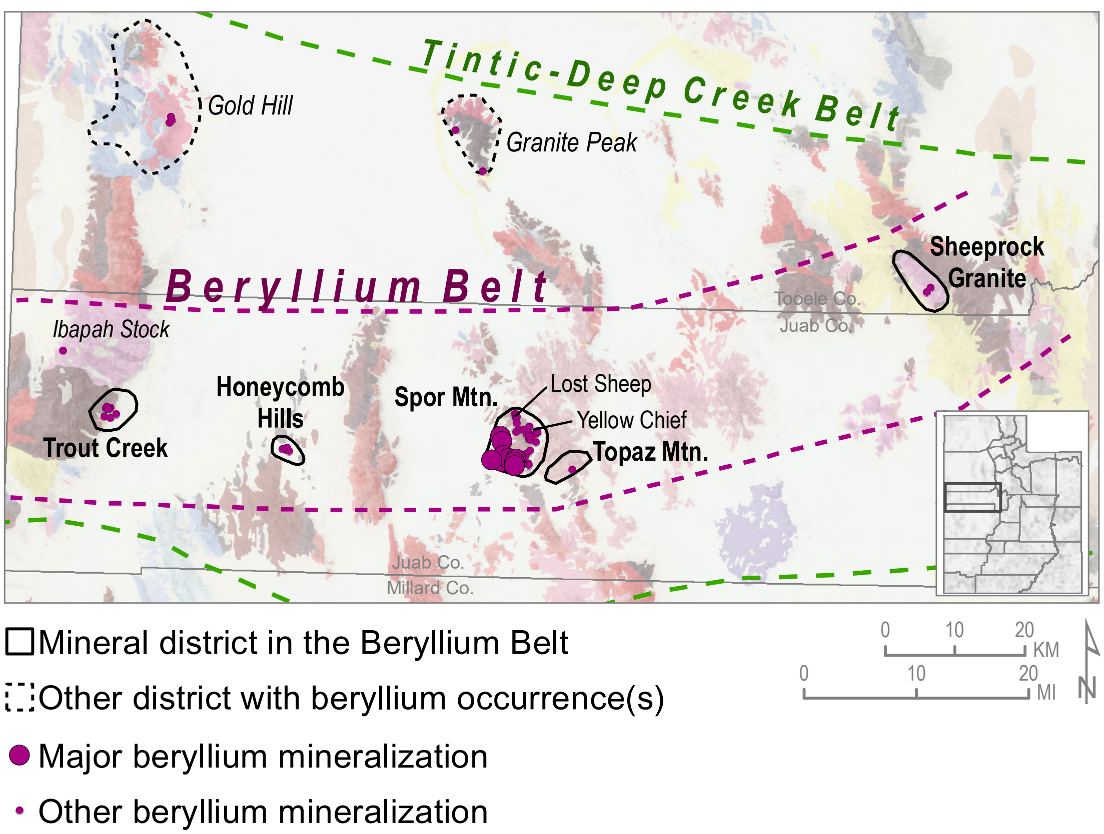

Figure 5. *The Beryllium Belt geologic province in Utah. Geology base map from Hintze and others (2000).*

to Miocene highly evolved high-silica topaz rhyolites and granites, is geographically coincident with the Tintic–Deep Creek mineral belt, a broader area of intermediate intrusive and volcanic rocks of Eocene to early Oligocene age influenced by deep-seated basement structures. The two belts are likely related on a geologic continuum, but the common usage is that the Tintic–Deep Creek belt refers to the large trend of precious and base metal mineralization related to porphyry, skarn, and replacement style deposits, whereas the Beryllium Belt refers to a smaller area of highly evolved intrusive and volcanic chemistries.

The Beryllium Belt consists, from east to west, of the Sheeprock granite, Topaz Mountain, Spor Mountain, Honeycomb Hills, and the Trout Creek area of the southern Deep Creek Range. This belt is characterized by highly evolved late Oligocene and Miocene intrusive (Sheeprock Granite, Trout Creek) or volcanic (Topaz Mountain, Spor Mountain, Honeycomb Hills) rocks that also host uranium, fluorite, lithium, and REE enrichment. Beryllium occurs as beryl in the Sheeprock Granite, Topaz Mountain, and Trout Creek area and as bertrandite at Spor Mountain and Honeycomb Hills. Uranium mineralization is found on the eastern flank of Spor Mountain at the Yellow Chief mine, and fluorite has been mined from breccia pipes at the Lost Sheep mine (see Fluorspar section). Though occurring north of the main Beryllium Belt trend, the Rodenhouse Wash area of the Gold Hill mining district has notable beryllium enrichment in quartz-adularia-carbonate veins associated with silicic Miocene volcanics, and beryl has been noted in pegmatites of the Granite Peak district. Pegmatitic beryl was also noted in one location of the Ibapah stock northwest of the Trout Creek area. The Spor Mountain district is the most significant area for beryllium mineralization and is the only area that has been mined for beryllium ore. Minor mining for gem-quality beryl has occurred at various sites including Topaz Mountain and the Ibapah stock.

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Lithium

Overview and Criticality

Lithium is a key component in rechargeable lithium-ion batteries, making it essential to many modern technologies such as portable electronic devices and electric vehicles. The demand for and price of lithium have both risen sharply in the past several years in response to increasing battery demand. Beyond batteries, lithium is also used for glass and ceramic production, lubricating grease, pharmaceuticals, and a variety of other applications. Lithium is produced in the form of lithium carbonate (Li_2CO_3), lithium hydroxide (LiOH), or lithium chloride (LiCl). Lithium's criticality is linked to the country's reliance on imports (currently over 25%) and its use in many technological applications, particularly "green technologies," along with being a component in certain types of nuclear reactors and aerospace alloys.

Sources and Geology

Lithium is produced from two primary geologic sources: continental brines and igneous pegmatites. Lithium clays, such as hectorite, represent another geologic source, but clays are not currently significant for lithium production. Globally, the largest producers of lithium are Australia, Chile, China, and Argentina. Lithium from Australia is sourced from pegmatites, which are the product of evolved magmas and are enriched in lithophile elements, hence the presence of lithium. The most important lithium ore mineral in pegmatites is spodumene ($LiAlSi_2O_6$), but lepidolite ($K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$), petalite ($LiAlSi_4O_{10}$), and a few others have also been sources.

Although Australia is currently the largest lithium producer, the majority of the world's resources are held in brines of the "lithium triangle" in South America which includes parts of Argentina, Bolivia, and Chile. In some areas within the lithium triangle, average concentrations of lithium in brines can reach up to 1400 ppm. Lithium concentrates in brines due to its relatively incompatible chemical nature; it behaves as a conservative solute in aqueous systems (like Na and Cl), and is excluded from almost all solids such that precipitation of halite (NaCl) serves to concentrate Li in the residual brine. Lithium-rich brines also require a source of lithium, often in the form of volcanic rocks, lithium-rich clay, or other sedimentary deposits from which brines can leach and concentrate lithium. Domestic lithium production comes from brines in Nevada and Utah. Average concentrations of lithium in the productive brines in Nevada are around 160 ppm (maximum was ~380 ppm prior to brine extraction), which is on the low end of concentrations for global lithium-from-brine producers. In Utah, lithium is a byproduct of magnesium metal production from Great Salt Lake brines.

Lithium in Utah

Rising demand for and price of lithium has led to a corresponding rise of interest in Utah's potential resources, and most of the attention has been focused on Utah's brine resources (figure 6). Several of Utah's brines have anomalous lithium, and areas that have drawn interest include Great Salt Lake, the Paradox Basin, and the Bonneville Salt Flats. However, concentrations of lithium in Utah's brines are below or on the low end of what has generally been considered economic. Another challenge for Utah's brines is that they generally have high levels of other ions, such as magnesium, that make processing difficult and expensive. Current technology employed by most commercial producers has a maximum threshold of magnesium-to-lithium ratios of around 10 to 1, but Utah's brines are typically higher than 40 to 1. However, several companies are seeking to develop what is termed "direct lithium extraction" (DLE) technologies that hope to overcome some of the processing issues of brines with challenging chemistry. DLE technology remains up-and-coming and has not been broadly proven or employed in commercial production; questions also exist about energy and freshwater consumption related to DLE processing.

Notably though, US Magnesium began producing lithium as a byproduct of their magnesium operation at Great Salt Lake in 2020, becoming one of only two active producers in the United States. Based on historical data, maximum measured lithium concentrations in Great Salt Lake are around 80 ppm (lithium concentration varies with location and lake level, and the average concentration is less than 80 ppm), which is below the average grade of current global lithium producers. Despite high magnesium concentrations in Great Salt Lake, part of US Magnesium's production process requires separation of lithium from the magnesium-rich brine feedstock, allowing them to produce lithium economically. US Magnesium continues to produce lithium and is working towards their capacity of 10,000 tons of lithium carbonate. Compass Minerals, a potash producer processing brine from the north arm of the lake, intends to begin lithium production by 2025 using DLE technology. To that end, they have defined a lithium carbonate resource of 2.6 million tons that includes the entire Great Salt Lake as well as interstitial brines below/in their evaporation ponds (2.55 million tons just within the lake). Compass Minerals does not have exclusive rights to the lithium in Great Salt Lake and how much of the defined resource is extractable is undetermined.

In the deep subsurface of the Paradox Basin in southeast Utah, the Pennsylvanian Paradox Formation and units below contain groundwater brines. Lithium enrichment in these subsurface brines is likely to be somewhat coincident with the extent of potash mineralization in the Paradox Basin (figure 6). Old analyses of brines from oil and gas wells show lithium concentrations reaching the low hundreds of parts per million, and in recent years, Anson Resources has re-entered abandoned oil and gas wells and encountered lithium concentrations of up to 250 ppm in subsurface brines. A recent resource estimate from Anson in an area west of Moab (Paradox Lithium project) contains an in-place indicated and inferred resource of 1 million tons of lithium carbonate equivalent, but recoverable lithium remains undetermined. Average concentrations of lithium in their target horizons are estimated to range from about 80 to 180 ppm. Other companies are also evaluating brine resources elsewhere in the Paradox Basin and in the Great Salt Lake Desert. In the Great Salt Lake Desert, the Bonneville Salt Flats and Pilot Valley have drawn interest and subsurface brines in those areas show lithium concentrations of up to about 140 ppm and 100 ppm, respectively, but average concentrations are likely lower. The Great Salt Lake Desert is represented by areas geologically mapped as playa mud where subsurface brine may be present (figure 6); however, resource potential is limited in many parts of the playa and is highest in areas that have more concentrated brines such as the Bonneville Salt Flats. As previously noted, production from Utah's brines would likely require functionally scalable DLE technology. Existing producers of other commodities from brines and evaporites may be the most likely future lithium producers in Utah as lithium concentrates in their evaporative processes.

Beyond brines, minor activity in Utah has focused on potential rock-hosted lithium resources. In the Honeycomb Hills area in Juab County, a company has been evaluating lithium potential in volcanic tuffs having clay alteration. Recent channel sampling of the altered tuffs has shown an 80-foot interval at nearly 1400 ppm lithium, but the extent of this potential resource is currently undefined. Rocks associated with the highly evolved magmatic system that produced beryllium and fluorspar deposits in the Spor Mountain area may also be a source of lithium interest in the future.

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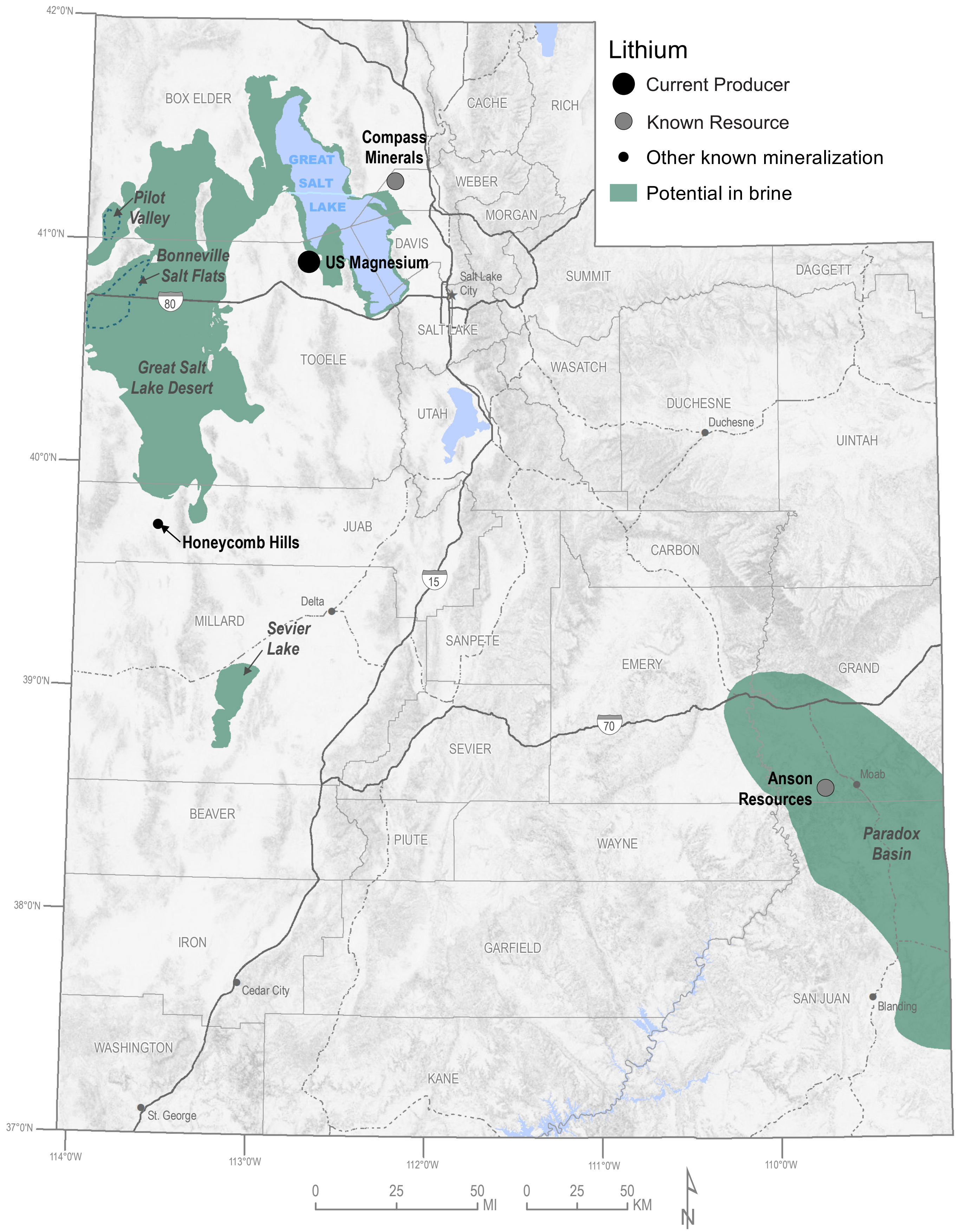

Figure 6. *Lithium mineralization in Utah.*

Utah Spotlight: Great Salt Lake

Around 13,000 years ago, the desiccation of Lake Bonneville, which covered much of northwestern Utah, resulted in a lake roughly the size of today's Great Salt Lake, and Great Salt Lake remains a significant feature of Utah's physiographic, geological, and mineralogical landscape (figure 7). The terminal or closed basin nature of the lake has caused accumulation and concentration of dissolved solids, and salinity in the lake varies with location and lake level. As the lake goes up and down, an inversely corresponding change in the saltiness occurs. A railroad causeway that roughly bisects the lake has also led to the north arm of the lake being much saltier than the south arm, and the north arm is salty enough that formation (or precipitation) of halite (NaCl) is a common occurrence. Overall, the concentrated brine of the lake allows for economic extraction of multiple mineral commodities, and although the majority of the dissolved solids in the lake are sodium and chloride, the lake also has high levels of magnesium, potassium, and sulfate. In addition to extraction of magnesium, the potassium and sulfate in the lake are used to produce potash in the form of potassium sulfate. Prior to 2022, potash was on the USGS's critical mineral list. As noted in the preceding lithium section, Great Salt Lake is also a source of byproduct lithium from US Magnesium's magnesium metal production. Great Salt Lake also has a tie-in to titanium production. A titanium facility is adjacent to US Magnesium's plant because magnesium metal is an important ingredient in the kroll process to produce titanium sponge, a raw form of titanium metal. However, the titanium is not sourced from the lake and comes from out-of-state. The titanium plant has been idle for the past few years but could be recommissioned if titanium sponge prices rise.

Great Salt Lake has been in the news recently as it reached new historical lows in both 2021 and 2022; the previous low was in 1963. In late 2022, the south arm of Great Salt Lake dipped to about 4188.5 feet and was nearly 3 feet below the low recorded in 1963. The recent record lows have been caused by drought and upstream diversions, and low lake levels are beginning to negatively affect the lake's ecosystem and industries. Managing agencies, lake stakeholders, governing entities, and other organizations are seeking solutions to stabilize water levels by ensuring more water reaches the lake.

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Figure 7. *Great Salt Lake's north arm showing slushy mirabilite, a hydrous sodium sulfate mineral that forms in the winter and dissolves in the spring when temperature rises. Photograph was taken near the Spiral Jetty.*

Magnesium

Overview and Criticality

Magnesium is the 12th element on the periodic table (figure 1) and is the 8th most abundant element in the earth's crust. Magnesium has several applications depending on what form it takes. Magnesium metal, magnesium chloride, magnesium hydroxide, caustic-calcined magnesia, and others are all magnesium-based products; however, magnesium metal is the form considered to be a critical mineral. A significant use of magnesium metal is in alloys; magnesium can add strength, decrease weight, and increase corrosion resistance. Magnesium metal is commonly alloyed with aluminum for aerospace and defense applications and is important in the manufacture of several common products, for example, automobile components, soda cans, and fireworks. Use of magnesium in auto parts has recently increased as auto manufacturers work to reduce the overall weight of vehicles. For certain titanium manufacturing processes, magnesium metal is an essential ingredient, linking its criticality to domestic titanium production. Another significant aspect of magnesium's criticality is that primary magnesium metal is produced at only one facility in the United States (located in Utah), creating a single point of supply-chain failure.

Sources and Geology

Several sources of magnesium exist but, economically, some of the most important are surface and subsurface brines (including seawater), dolomite, and magnesite. Magnesium is a common component of dissolved solids in water and is the third most significant component of solids in seawater after sodium and chloride. Continental brines are also often enriched in magnesium. Surface brines, commonly found in terminal lakes or terminal basins, are a common source of magnesium. Examples of surface brines include Great Salt Lake in Utah and the Dead Sea in Israel and Jordan. Currently, the only primary production of magnesium metal in the United States is from surface brine at Great Salt Lake.

Dolomite is a carbonate sedimentary rock which is composed of the mineral of the same name (dolomite, $CaMg[CO_3]_2$). Dolomite, as a rock, is very common and numerous large, relatively pure deposits are known worldwide. Historically, dolomite was used to produce magnesium metal in the United States, but is not currently being mined for that. Magnesite ($MgCO_3$), though much less common than dolomite, is similar in composition but contains no calcium. Magnesite deposits are formed through the alteration of other rocks such as limestone and peridotite. Olivine is another mineral that can be magnesium-rich with a composition of $(Mg, Fe)SiO_4$, and it commonly occurs in mafic igneous rocks such as basalt, gabbro, or peridotite.

Globally, resources of magnesium are plentiful and sufficient to meet required demands of magnesium metal, and China is the leading producer. The United States imports about half of its domestic requirement for magnesium metal, primarily sourced from Canada and Israel.

Magnesium in Utah

Utah is the only primary producer of magnesium metal in the United States, produced at US Magnesium's facility located on Great Salt Lake (figures 8 and 9). Magnesium concentration in the lake brine is relatively high, but the concentration varies with lake level and over time as a function of the lake's dynamics. Magnesium accounts for more than 3% of the dissolved solids in the lake brine. Ocean water has about 3.5 wt. % dissolved solids, but the part of Great Salt Lake that feeds the magnesium facility averages around 13 wt. % dissolved solids. To produce magnesium metal, the lake's magnesium-rich brine is further concentrated in a series of evaporation ponds and the enriched brine is the feedstock of an electrolytic process that converts magnesium chloride to magnesium metal. The approximate capacity of the facility is about 75,000 tons of magnesium metal per year and the magnesium resource in the lake will likely last for several decades. The current trend of receding lake level may be a greater limiting factor to production than reduced magnesium levels in the brine (see Utah Spotlight: Great Salt Lake). Construction of Utah's magnesium plant at Great Salt Lake began in 1970 and startup followed in 1972. From 1972 through about 1995, magnesium operations and production at the lake experienced a variety of problems: high capital costs, process difficulties, low productivity, high lake levels, and changing ownership. However, by 1995, production stabilized and has been steady since.

Beyond Great Salt Lake, several other potential magnesium resources are present in Utah. Subsurface, magnesium-rich brines are found in a variety of places: the Great Salt Lake Desert, which includes the Bonneville Salt Flats; Sevier Lake (or Sevier Playa); and the Paradox Basin (figure 8). Brines in the Great Salt Lake Desert and Sevier Lake are genetically related to the recent desiccation of the late Pleistocene Lake Bonneville system, and brines in the Paradox Basin are related to deep, subsurface, cyclically bedded evaporites that formed in a restricted marine basin during the Pennsylvanian (around 300 Ma). In the Paradox Basin, magnesium enrichment in brines is likely to be roughly coincident with the extent of potash mineralization. Currently, brines of Great Salt Lake and the Bonneville Salt Flats are used to produce magnesium chloride, another commodity with a high magnesium content that is used for dust control and road deicing.

Utah also has extensive potential resources of high-purity dolomite. Several Paleozoic rock units have high-purity dolomite including the Cambrian Notch Peak Formation and limestone of the Cricket Mountains, the Ordovician Ely Springs and Fish Haven Dolomites, and the Silurian Laketown Dolomite, and these units are widely distributed in northern and western Utah. Currently, dolomitic lime, another magnesium commodity, is produced by Graymont from a Cambrian high-purity dolomite deposit in the Cricket Mountains in Millard

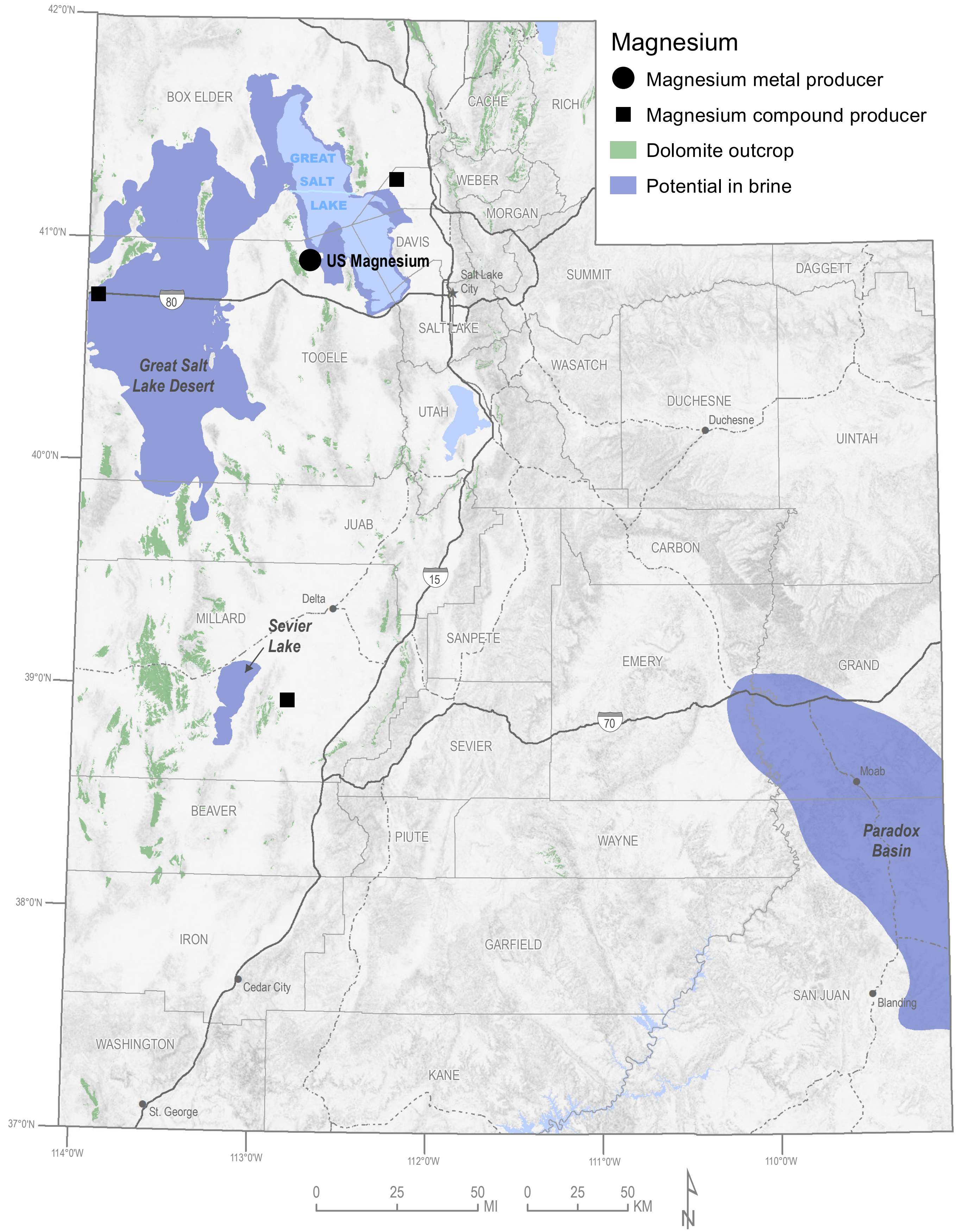

Figure 8. *Magnesium mineralization in Utah.*

Figure 9. *US Magnesium's operation on the west side of Great Salt Lake looking northeast, taken 2015. Photo courtesy of Don Clark.*

County. Dolomitic lime is used in steelmaking, water treatment, environmental applications, and in other ways. In the past, magnesium products have also been produced from the Ely Springs Dolomite and the Notch Peak Formation in Utah.

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Platinum and Palladium

Overview and Criticality

Platinum and palladium are part of a group of elements on the periodic table known as the Platinum Group Elements, or PGEs. This group of metallic elements, which also includes rhodium, ruthenium, iridium, and osmium, share many similar physical and chemical properties, such as high melting points, resistance to erosion, and the ability to act as a catalyst. These elements often occur together in nature; however, platinum and palladium are the most common and hence are grouped separately here.

Though often thought of as precious metals for their use in currency and jewelry, platinum and palladium are primarily used in industrial applications. The main use for both platinum and palladium globally and in the United States is in automotive catalytic converters to reduce harmful emissions in vehicle exhaust such as carbon monoxide and nitrous oxide. Their role in reducing vehicle emissions makes both elements important in a consumer market increasingly concerned with environmental factors such as air quality. Platinum and palladium are also used in fiberglass and flat panel displays, as hard and durable alloys, and in electrical components of most modern devices, such as laptops and smartphones. The United States produces platinum and palladium from a mine in Montana, and as a byproduct of copper-nickel mining in Michigan. However, these sources are not enough to cover domestic needs and nearly all platinum and 85% of palladium is imported. Considering their necessity to a multitude of everyday items and the relative geologic scarcity, they are considered critical.

Sources and Geology

Platinum and palladium are among the rarest elements in the earth's crust and are concentrated in only a few geologic locations globally. Magmatic sulfide deposits are the main deposit type where PGEs are found in economic concentrations, which are associated with large-scale mafic or ultramafic magmas known as large igneous provinces (LIPs). The magmas in these districts are often enriched in metals found more commonly in the mantle than in the crust, and if they are emplaced under the right conditions they form what is known as a monosulfide solid solution that consists almost exclusively of metals like gold, copper, platinum, and palladium in a sulfide liquid. When the magma cools, the resultant crystallized form of this liquid can be mined as high-grade ore. Examples of world-class PGE deposits include Bushveld in South Africa, Noril'sk in Russia, and Sudbury in Canada. The United States imports the majority of its palladium from South Africa and Russia, and most platinum from South Africa. Although magmatic sulfide deposits are the only primary source of platinum and palladium, both can be produced as byproducts from magmatic-hydrothermal systems like porphyry deposits and from sedimentary-hydrothermal systems like manganese crusts on seamounts.

PGEs in Utah

Utah does not have any magmatic sulfide deposits or LIPs, hence platinum and palladium are produced in Utah as byproducts of porphyry copper mining at Bingham Canyon (figures 10 and 11). Porphyry deposits are often influenced by mixing between calc-alkaline magma systems, which drive overall magmatic emplacement into the crust, and mafic magmas similar to those found in magmatic sulfide deposits, which contribute sulfur and metals (Au, Pt, Pd) to ore-forming processes. Because it formed in a continental arc setting where mafic magma input is limited (versus island arc settings for porphyry formation), by global porphyry standards Bingham Canyon hosts almost no enrichment in platinum or palladium (figure 12). However, despite the low levels of platinum and palladium in Bingham Canyon ores, the modern copper refining process is sophisticated enough to isolate whatever concentrations of PGEs are available. Impurities in copper ores such as gold,

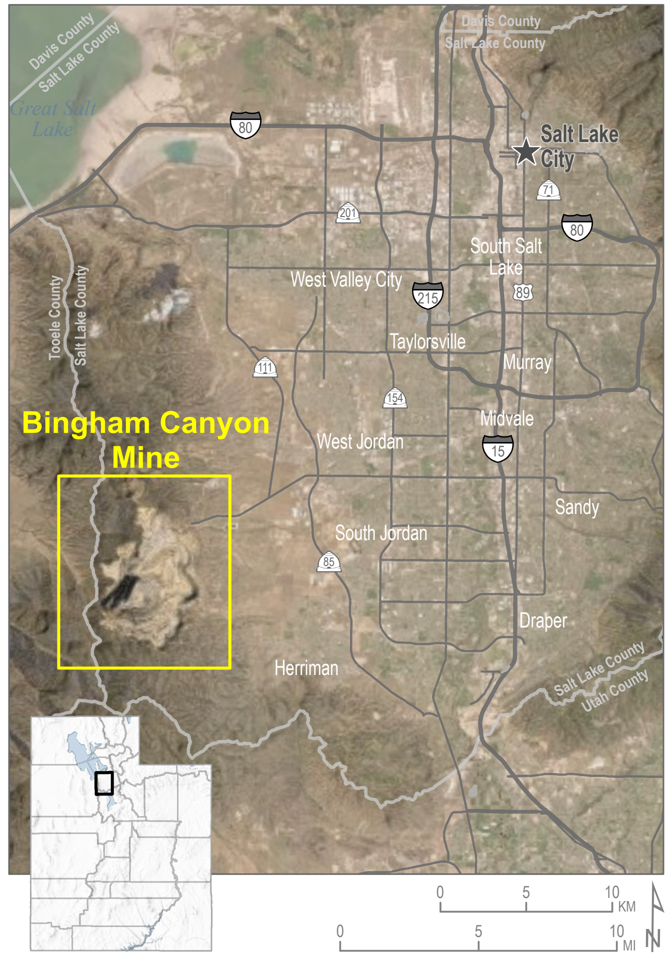

Figure 10. *Location of the world-class Bingham Canyon mine west of Salt Lake City.*

silver, bismuth, tellurium, selenium, platinum, and palladium are removed during the process that creates high-purity copper cathodes, and from these impurities gold, silver, lead carbonate, and crude selenium are recovered. Platinum and palladium are concentrated in the crude selenium product and refinement to their native metal forms is completed by consumers.

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Figure 11. *The open pit at Bingham Canyon mine looking south, taken June 2017.*

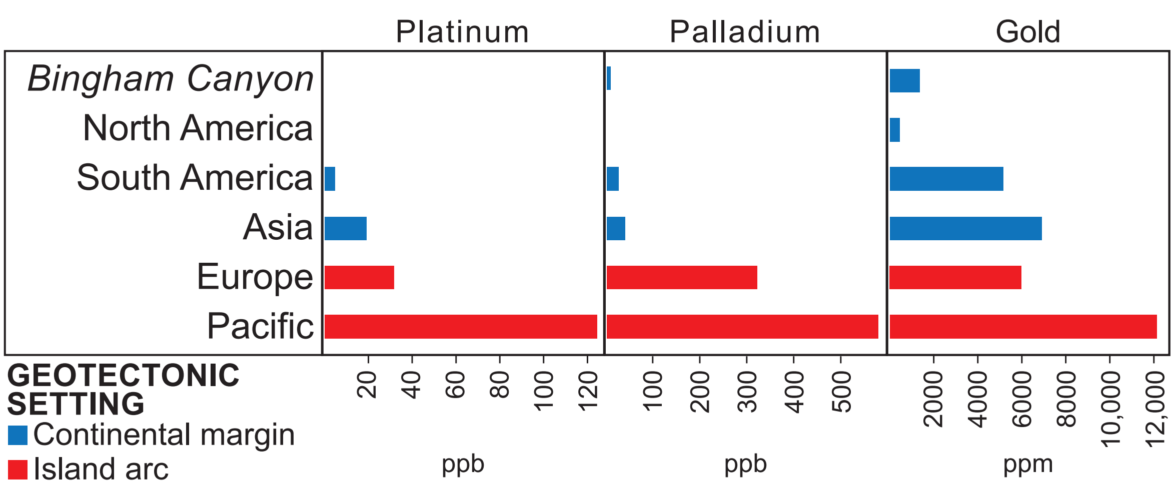

Figure 12. *Comparison of platinum, palladium, and gold content in global porphyries. Adapted from Tarkian and Stribny (1999).*

Utah Spotlight: Bingham Canyon

The Bingham mining district (including the Bingham Canyon, Lark, and Barney's Canyon mines, among others) is the most historically productive mining district in the United States and has been mined continuously for over 150 years. The Bingham Canyon mine was the first copper porphyry deposit ever mined and helped to usher in a new era of mining low-grade, high-tonnage deposits in the early 1900s, which is the dominant economic model for copper mining today. To date, Bingham Canyon remains the second largest copper producer in the United States. Not only is ore mined from Bingham Canyon, it is also refined in Salt Lake County. In fact, the Kennecott smelter is one of only two primary copper smelters in the United States.

The ore from the Bingham Canyon open-pit mine is crushed by an in-pit crusher so that it can be transported by conveyor belt to the concentration facility near Copperton, Utah (figure 13). At the concentrator, the ore is ground to a very fine rock flour and put through a flotation process, which separates out copper concentrate, molybdenum concentrate, and silicate waste material. The copper concentrate is sent by pipeline to the smelter at the north end of the Oquirrh Mountains, the molybdenum concentrate is dried, bagged, and sent to domestic and international molybdenum refineries, and the silicate waste is sent by pipeline to a tailings impoundment north of Magna, Utah. At the smelter the copper concentrate goes through three smelting steps: a flash smelting furnace produces copper matte, a flash converting furnace produces more refined blister copper, and an anode refining furnace produces copper anodes of nearly pure copper. The copper anodes are then sent by rail to the refinery, where the anodes are put in an acidic electrolyte solution with a stainless steel cathode blank. A current is run through the solution for over a week, dissolving the copper from the anode and redepositing it as high-purity copper on the cathode. The impurities that are removed in this step sink to the bottom of the electrolyte cell and are referred to as slimes.

At the end of the copper-refining process, the high-purity copper cathodes are stacked, corrugated, and shipped. The slimes, which contain gold, silver, lead, selenium, tellurium, platinum, and palladium are sent to the precious metal refinery where gold, silver, and lead carbonate are recovered for sale. The other metals deport to the selenium "cake," which is sold for further processing by others.

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Tellurium

Overview and Criticality

Tellurium is a rare chalcophile metalloid, meaning it readily bonds with sulfur to form sulfide minerals which often host other important metals like copper and gold, and has characteristics of both metals and nonmetals. In recent years, tellurium demand has increased with the emergence of thin-film cadmium-telluride photovoltaics, which are an alternative to the currently dominant crystalline silica technologies due to high efficiency, low cost, and rapid manufacturing. The global photovoltaics industry accounts for 40%–60% of tellurium consumption. In addition to photovoltaic applications, tellurium is also used in thermoelectric products and as a metallurgical additive to improve performance of various alloys. Until the onset of tellurium recovery at Bingham Canyon in 2022, there was no fully domestic supply chain (mining through refining) of tellurium in the United States, hence the high import reliance and importance to energy technology make tellurium considered critical.

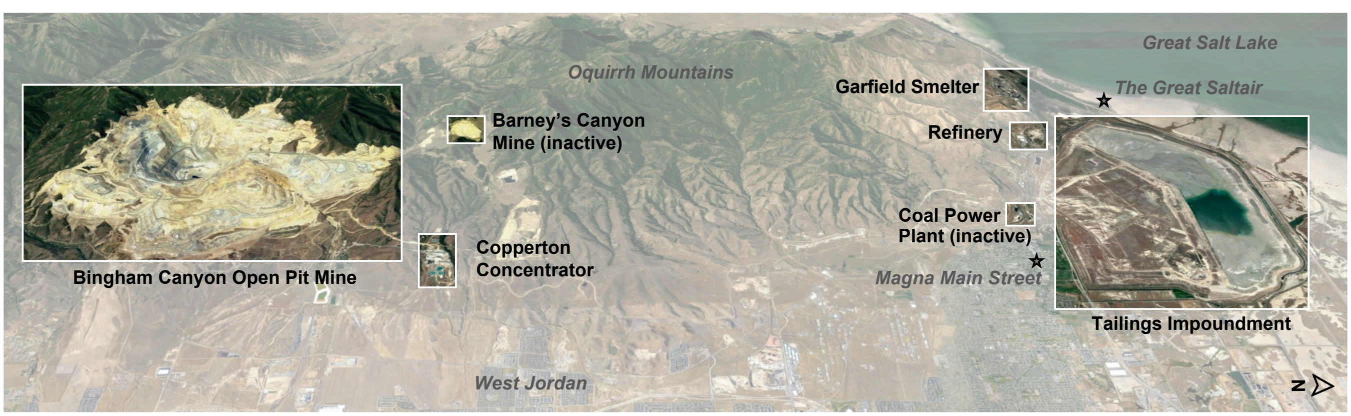

Figure 13. *The Kennecott Utah Copper Company operation west of Salt Lake City, looking west. Imagery from GoogleEarth, taken July 2019.*

Sources and Geology

Tellurium is a very rare element in the earth's crust, and is typically found in association with gold, though at lower concentrations. Most tellurium (as much as 90% globally) is recovered as a byproduct from copper mining. One of the few deposit types where telluride minerals can form in economic quantities is epithermal deposits, such as the Cripple Creek gold-telluride mine in Colorado. Cripple Creek contained significant amounts of gold hosted as the mineral calaverite, or gold telluride ($AuTe_2$). Cripple Creek's tellurium was so famous that another mining town (and eventually ski resort) in Colorado took the name Telluride, even though the deposits in that mining district were not strongly enriched in tellurium. There are no mines focused exclusively on tellurium anywhere in the world, though epithermal deposits located in China and Sweden extract tellurium as one of the primary commodities along with gold ± silver.

Tellurium in Utah

In May 2022, Bingham Canyon porphyry copper mine officially began recovery of tellurium as a byproduct of the copper refining process, becoming one of only two tellurium producers in the United States. Rio Tinto, the company that owns Bingham Canyon, estimates an annual production of up to 20 tons of tellurium, which would account for the majority of tellurium imported by the United States for consumption. Given the global tellurium market is relatively nascent, Bingham Canyon may become the sixth largest tellurium producer globally. The recovery of tellurium at Bingham Canyon is accomplished through an additional recovery circuit that uses copper chips, high temperatures, and mechanical agitation of the anode slimes (see Utah Spotlight: Bingham Canyon) to produce a copper telluride byproduct which is sold and further refined by another Utah company, 5N Plus. The tellurium in Bingham Canyon ores deports to copper sulfide minerals (figure 14) such as chalcopyrite (CuFeS), bornite (Cu_5FeS_4), and digenite (Cu_9S_5), though is not evenly distributed among those minerals (figure 15). A recent study of energy-critical elements at Bingham Canyon (Brodbeck and others, 2022) showed that tellurium preferentially occurs in digenite dissolved from bornite, mirroring the distribution of gold and roughly inverse to indium and bismuth (figure 15).

Although not currently considered economic, abundant tellurium-bearing minerals have been noted in the recent T2 high-grade gold discovery at the Trixie mine in the East Tintic district, Utah County. The Trixie mine is a high sulfidation structurally controlled stockwork vein system hosted in the Tintic Quartzite that has yielded individual samples in excess of 10,000 ppm gold. The T2 structure was discovered by Tintic Consolidated Minerals in 2020 while exploring the historic Trixie mine workings, and the T2 ore is uniquely characterized by native gold and exotic telluride and tellurate minerals such as xocomecatlite, which has a striking green color and is only known to occur in a handful of other locations globally (figure 14).

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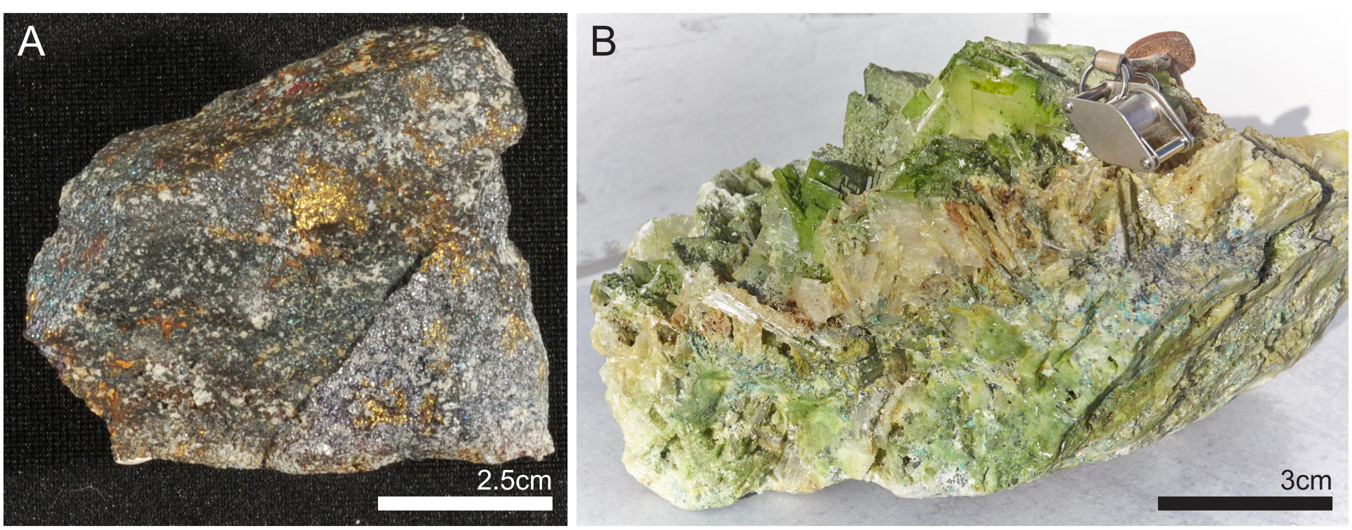

Figure 14. *High-grade Bingham Canyon copper ore and ultra-high grade Trixie gold ore.*

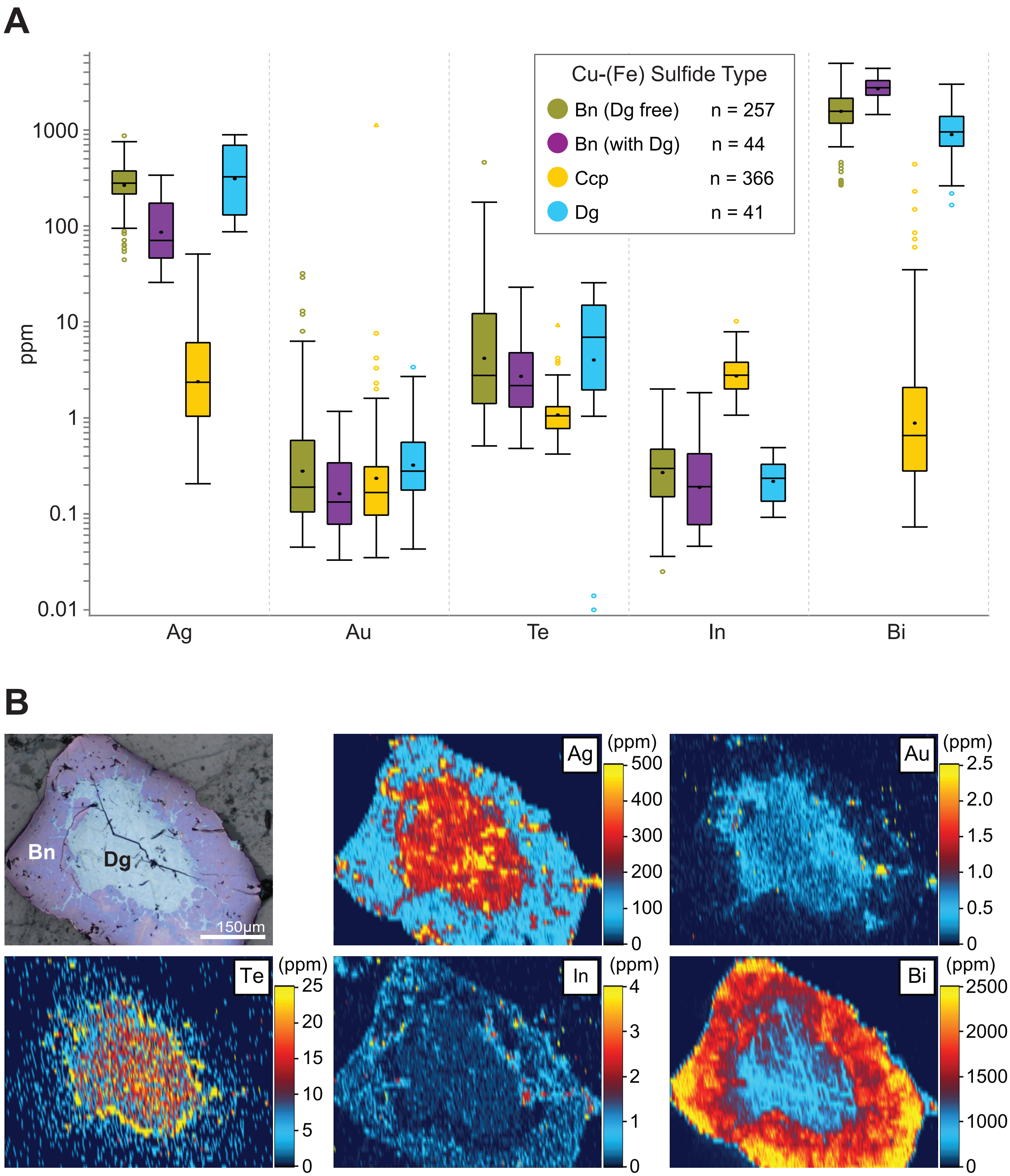

Figure 15. (A) *Average enrichment of critical minerals in copper-bearing minerals (bn = bornite, ccp = chalcopyrite, and dg = digenite), and* ***(B)*** *distribution of critical minerals in individual copper-bearing minerals from Bingham Canyon, modified from Brodbeck and others (2022).*

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KNOWN CRITICAL MINERAL RESOURCES IN UTAH

Aluminum

Overview and Criticality

Aluminum has numerous uses and applications. Aluminum alloys are widely used because of their lightweight and corrosion-resistant nature. Significant amounts of aluminum are used in transportation applications, packaging, building components, and electrical applications. Most people benefit from aluminum on a daily basis from its presence in cars, boats, airplanes, power transmission lines, food packaging, and electronics, to name just a few. Aluminum's criticality is linked to the import reliance of bauxite, which is the primary ore material for production of aluminum metal. Most of the United States' imported bauxite comes from Jamaica.

Sources and Geology

Globally, most aluminum is sourced from bauxite deposits, which contain a mixture of minerals such as aluminum hydroxides and iron oxides. Bauxite deposits are formed as a product of weathering various aluminum-containing source-rock types. The deposits most often develop in tropical or subtropical conditions at or near the surface. Several countries have significant bauxite reserves including Guinea, Vietnam, Australia, Brazil, and Jamaica. Currently, the largest bauxite producers are Australia, China, Guinea, Brazil, India, and Indonesia.

Although commercially bauxite is, by far, the most significant source for aluminum, alternative aluminum sources exist that could be used to produce aluminum. These sources include aluminum-bearing clays, shale, and aluminum. Overall, global aluminum resources are plentiful and sufficient to meet current and future needs and production dynamics will generally be driven by economics.

Aluminum in Utah

No substantial production of aluminum has occurred in Utah, but the state has notable aluminum resources (figure 16). In fact, Utah boasts the largest aluminum deposit in the country. Alunite is a hydroxylated potassium aluminum sulfate mineral ($KAl_3[SO_4]_2[OH]$, figure 17), and Utah hosts two main types of alunite: vein and replacement deposits. Vein deposits tend to be higher grade but generally represent a smaller resource, and replacement deposits are lower grade but can represent large tonnages. Vein deposits of alunite from the Marysvale area were a source of potash (potassium compounds used primarily for fertilizer) during World War I and were evaluated as a source of aluminum during World War II. A small amount of alumina (Al_2O_3) was produced at that time but not at a commercial scale.

The largest known alunite deposit in the United States, the Blawn Mountain deposit, is located in Beaver County in the Wah Wah Mountains. This replacement deposit was first evaluated in the 1970s but has been reevaluated in the past decade as a source of potash as potassium sulfate; alumina would be a byproduct or co-product. A technical report, released in 2017, estimated the in-place measured and indicated resource of alumina in alunite at the Blawn Mountain deposit to be 56 million tons. The measured and indicated alumina resource from alunite in run-of-mine tons (based on potassium sulfate mining), which may better represent recoverable alumina, is about 19 million tons. Along with the Blawn Mountain deposit, other scattered vein and replacement deposits are known in southwestern Utah (Beaver, Piute, and Iron Counties), but these deposits are not as well defined. Utah's vein deposits would likely only serve as a high-grade alternate feed for operations based at larger replacement deposits. Beyond alunite, Utah has aluminum potential in some clay and shale deposits, but these deposits are unlikely to be economic as an aluminum source and are currently poorly defined.

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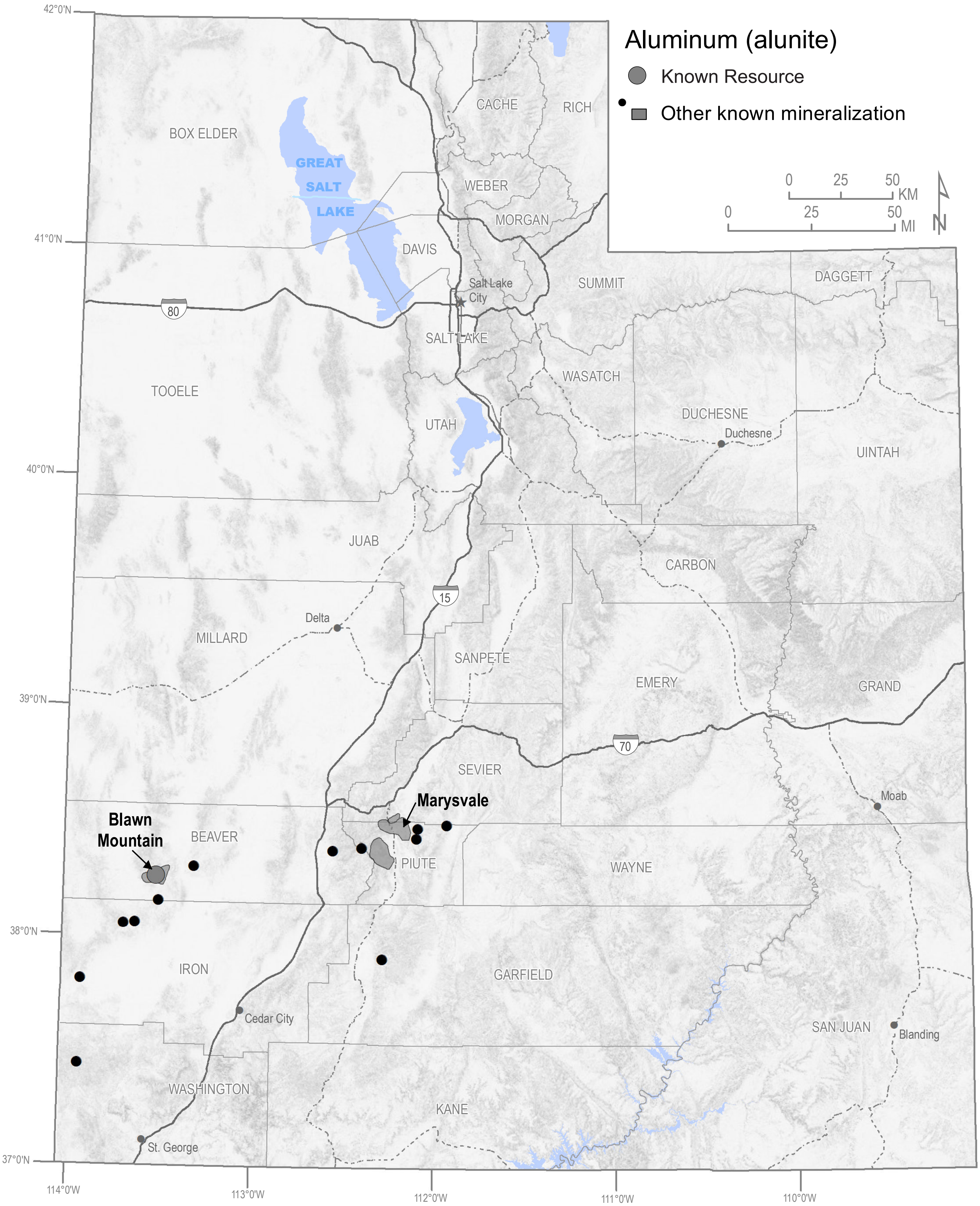

Figure 16. Alunite mineralization in Utah.

Figure 17. *Alunite vein in massive quartz-alunite sample from Blawn Mountain.*

Fluorspar

Overview and Criticality

Fluorspar is the commercial name for ore containing the mineral fluorite (CaF_2). In the United States, fluorspar is used to make hydrofluoric acid (HF), which is used to produce aluminum, uranium, and a variety of fluorine-bearing chemicals. Steel, cement, glass, ceramic, and enamel production also utilizes fluorspar. An aspect of fluorspar's criticality is the country's near complete reliance on imports from relatively few suppliers; only a negligible amount is produced domestically. In the past few years, nearly 70% of the fluorspar consumed in the United States came from Mexico.

Sources and Geology

Fluorspar is sourced from a variety of different deposit types including fissure veins, stratiform deposits, replacement deposits, stockworks, carbonatite and alkalic rock complexes, residual deposits, breccia pipes, and others. Commercial fluorspar deposits are often hydrothermal in origin. Most fluorspar is currently produced in China, but Mexico boasts the largest reserves. Significant reserves are also found in China, South Africa, and Mongolia.

Fluorspar in Utah

Utah has a history of producing fluorspar and new production is in development. As of 1975, Utah had produced around 250,000 tons of fluorspar, and some fluorspar has been mined since then but the amount has not been well documented. Fluorite deposits in Utah include breccia pipe fillings and replacements, fissure veins, skarn and tactite deposits, and disseminations in sedimentary and volcanic rocks, and nearly all of the deposits are Tertiary in age (between 2.5 and 66 Ma). Most of the fluorspar produced in Utah came from the Spor Mountain mining district where most of the shipped ore is reported to have ranged in grade from 60% to 95% fluorite (figure 18). The predominant deposit type at Spor Mountain is breccia pipe fillings and replacements in dolomites adjacent to faults, and the fluorspar occurs in a variety of ore textures: pulverulent, boxwork ore, aphanitic, sponge, and crystalline (figure 19). Although substantially less than the Spor Mountain district, most of Utah's remaining production came from the Washington, Blawn Mountain, and Star-North Star mining districts in Beaver County. Overall, the extent of Utah's fluorite resources are poorly defined, but the Spor Mountain area has the highest potential.

The largest past-producing fluorspar mine in Utah is the Lost Sheep mine in the Spor Mountain mining district. From 1948 through 1980, the mine produced about 160,000 tons of

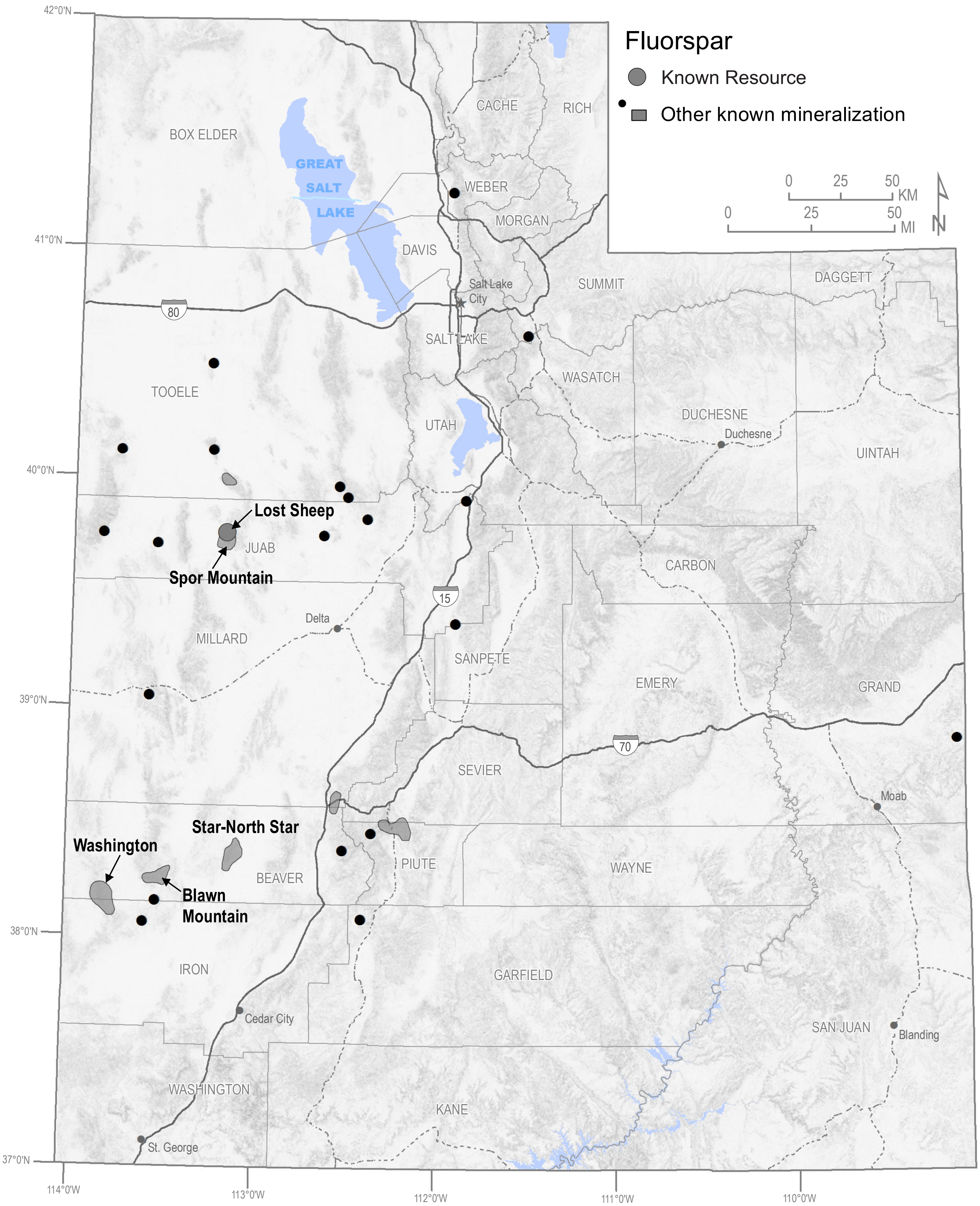

Figure 18. Fluorspar mineralization in Utah.

Figure 19. *Fluorite replacing Paleozoic coral fragments from Spor Mountain district. Photo courtesy of Mark Milligan.*

fluorspar, and an additional 8000+ tons was produced from 1993 to 2007. The remaining minable resource at the mine is unknown, but a company is currently delineating that resource as well as nearby potential resources at Spor Mountain through drilling, mapping, sampling, and geophysical surveys. They intend to restart production soon and are currently constructing processing facilities nearby in Delta, Utah.

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Germanium and Gallium

Overview and Criticality

Germanium is a metalloid, like tellurium, whereas gallium is a post-transition metal, meaning it is still considered a metal but is softer and has a lower melting point than many other metals. Both elements have the unique characteristic of being denser as a liquid than as a solid, like ice and water. Germanium and gallium are grouped here because they are often recovered together as byproducts of base metal mining, particularly in the United States. Over one-half of domestic consumption of germanium is for infrared optics and fiber-optic systems (e.g., internet cables), but an increasingly important role of germanium is in transistors of quantum computers and as a wafer substrate in multijunction solar cells, which are used in space applications. Gallium is used as gallium arsenide in compound semiconductor wafers, which are used in integrated circuits and optoelectronic devices such as LEDs and solar cells, though it is estimated that the current majority of gallium is used in smartphones and other computer devices. Germanium-bearing zinc concentrate is produced at mines in Alaska and Tennessee; however, the concentrates are exported outside the United States for further processing. The company 5N Plus in St. George imports recycled, scrap, and/or low-purity material to produce germanium wafers and refined gallium, but no domestic supply chain for either commodity exists. The criticality of germanium and gallium is based on both being critical to technological, energy, and defense applications with high import reliance.

Sources and Geology

Germanium has no specific geologic deposit type, rather it is recovered as a byproduct from zinc, silver, lead, and copper ores from a variety of deposit types. Gallium is often present in these ores as well, but currently more than 80% of gallium is produced as a byproduct of bauxite mining, where the primary commodity is aluminum (see Aluminum section). Germanium and gallium both occur commonly in the zinc ore mineral sphalerite (ZnS) across a range of deposits, but the concentrations are higher in low-temperature zinc-bearing carbonate replacement or sediment-hosted deposits with least input from magmatic systems, such as Mississippi Valley Type (MVT) and sedimentary exhalative (SEDEX) deposits. MVT deposits are named after the Mississippi Valley area where these deposits were originally discovered, and the Southeast Missouri Lead District contains the highest concentration of galena (lead ore mineral, PbS) in the world. The Red Dog mine in Alaska is the second largest zinc deposit in the world and also produces germanium as a byproduct (though the ore is processed in Canada), and is an archetypal example of SEDEX mineralization.

Germanium and Gallium in Utah

The Apex mine located in Utah's Beaver Dam Mountains in Washington County produced copper, gallium, and germanium briefly from the late 1980s to early 1990s (figure 20). The Apex mine had previously been an intermittent copper, lead, and silver producer from 1884 to 1962, and the germanium and gallium was originally recognized in 1958. Apex is a fairly unique deposit style with mineralization forming in

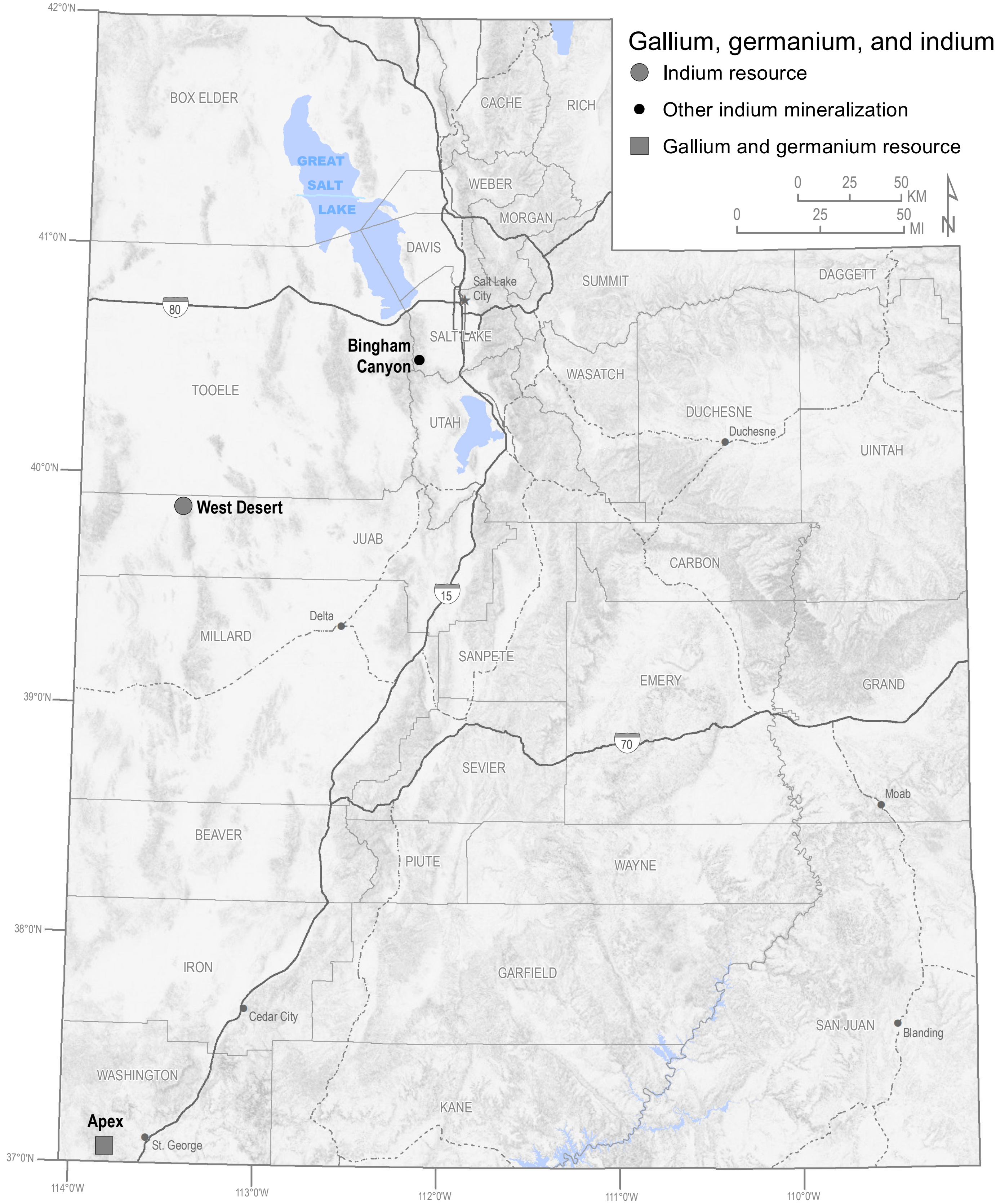

Figure 20. Indium, germanium, and gallium mineralization in Utah.

a steeply dipping pipe resulting from solution-collapse breccias in the Permian Pakoon Dolomite and Pennsylvanian Callville Limestone. Mine workings extended over 1400 ft in depth without reaching the bottom of the breccia pipe. Germanium and gallium are hosted in iron minerals (hematite, goethite, jarosite; figure 21), and the deposit still contains a roughly estimated 660,000 lbs gallium, 1.7 million lbs germanium, and 36 million lbs copper. Apex represents one of only two documented gallium resources in the United States (the other being Round Top, Texas). The Apex mine is currently owned by Teck, the same company that owns the Red Dog mine and produces germanium as a byproduct. Teck has not shown interest in developing the Apex, choosing rather to reclaim the mine following the final period of mining in the 1990s (figure 22). It is possible similar deposits exist in the area, and gallium-germanium geochemical anomalies are reported along a northwest trend up to 7 miles from the Apex mine itself. Solution-collapse breccia pipes can be "blind," meaning that they have no expression in overlying rocks at the surface. Solution-collapse breccia pipes have been identified elsewhere in the Beaver Dam Mountains and suggest that the underlying Mississippian Redwall Limestone developed an extensive karst system in the area, favorable for the formation of mineralized pipes like Apex (figure 22).

Figure 21. *High-grade Ge-Ga plumbojarosite ore from the Apex mine. Photo from Wenrich and Verbeek (2014), reproduced with the permission of Utah Geological Association.*

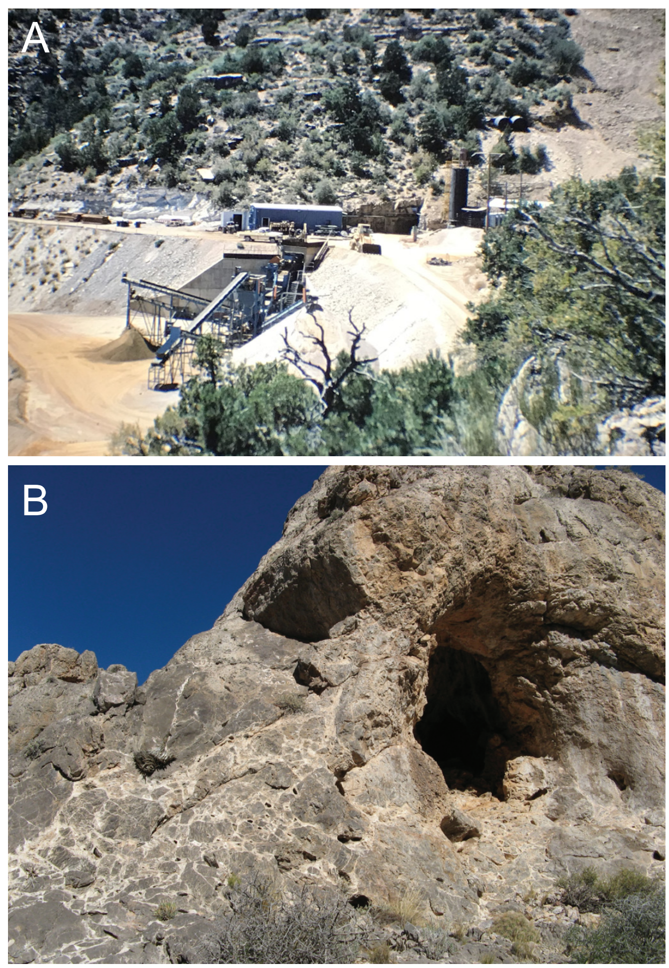

Figure 22. ***(A)*** *The Apex mine in operation in the 1980s, photo courtesy of Erich Petersen, and* ***(B)*** *dissolution cavity and brecciated limestone karst structures common in the Redwall Limestone, photo by Ken Krahulec.*

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Indium

Overview and Criticality

Indium is a soft silver-white metal that resembles tin, its neighbor on the periodic table. It was discovered in 1863 in sphalerite, the ore mineral for zinc. The new element was named indium for the brilliant blue, or indigo, of one of its spectral lines. The United States does not produce any indium domestically and is reliant on imports from China, Canada, Republic of Korea, and Taiwan to meet domestic demand. Indium's main use is as the major component in indium-tin oxide (ITO), which is an optically transparent and electrically conductive thin-film coating used in flat-panel displays, such as liquid crystal displays (LCDs); in other consumer electronics such as smartphones and laptops; and in infrastructure uses such as solar panels and alloys. Recent concerns over the long-term supply security of indium are fueling research into ITO alternatives, particularly given indium production is a byproduct of zinc production and hence indium supply cannot respond independently to increased demand. Given the total import reliance for the United States, the current ubiquity of indium requirements, and the lack of viable substitutes, indium is considered a critical mineral.

Sources and Geology

Indium is not recovered as a primary commodity, rather it is produced almost exclusively as a byproduct of zinc mining. The relationship between zinc mining and indium is because within the zinc ore mineral sphalerite (Zn(Fe)S), indium has a 3+ charge and couples with Cu, which has a 1+ charge, to replace zinc and/or iron, both of which have a 2+ charge for a total coupled substitution of 4+ charge. As such, the leading sources of indium are deposits with significant zinc mineralization, such as SEDEX and MVT deposits (see Germanium and Gallium). In addition to zinc deposits, indium also occurs in tin-rich polymetallic deposits that occur as veins and breccias in a variety of country rocks. Indium has been shown to account for nearly 7 wt. % of a sphalerite crystal in tin-rich polymetallic deposits, whereas the concentrations in SEDEX and MVT deposits tend to be less than 1 wt. %. Globally, most zinc and tin refining streams are not equipped to recover indium, so countries producing the most indium may not always be those with the highest geological reserves. China is currently the leading indium producer from a variety of zinc and tin deposits.

Indium in Utah

There are only three documented resources of indium in the United States, and two of them are in Utah (figure 20). Bingham Canyon hosts a very low level of indium enrichment (figure 15) that is not currently considered economic, as does the Morenci mine in Arizona, which is a porphyry copper deposit like Bingham. The largest known resource of indium in the United States, and the only deposit that has a formally established resource of indium, is Utah's West Desert skarn deposit. The West Desert zinc-copper-indium deposit (formerly known as the Crypto deposit) is located in the Fish Springs mining district in west central Juab County. West Desert is a skarn deposit related to the intrusion of an Eocene quartz monzonite, and mineralization occurs in shales interbedded with massive carbonates (Ordovician Wah Wah Limestone and Kanosh Shale; Corset Spring and Candland Shale Members of the Cambrian Orr Formation). Indium is hosted in sphalerite in concentrations

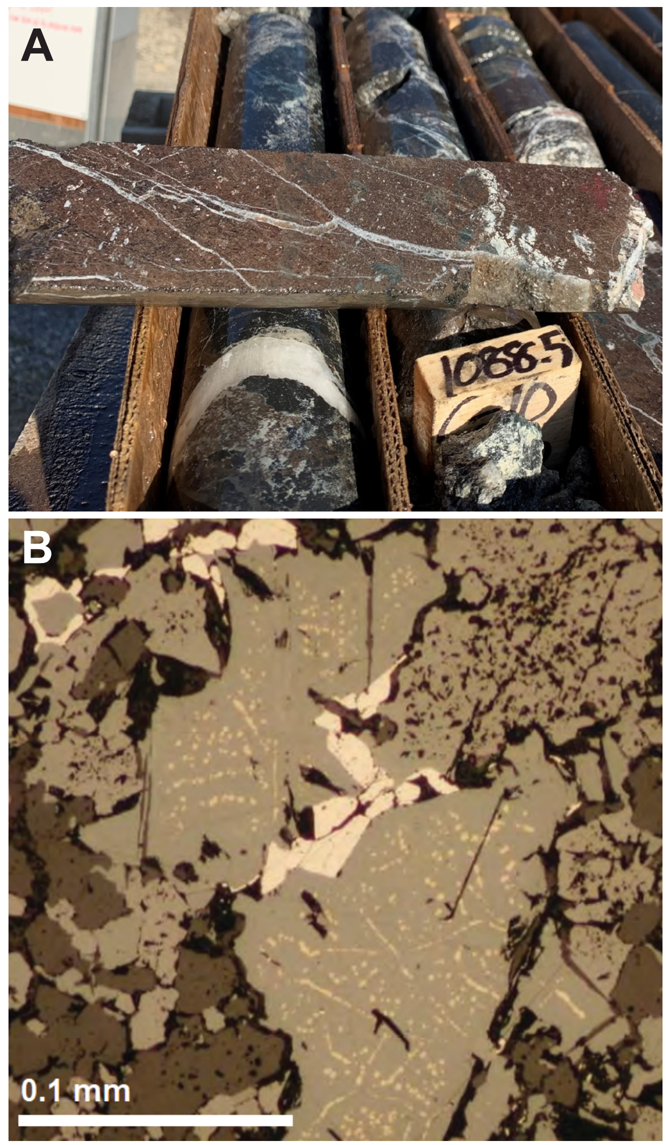

Figure 23. ***(A)*** *Indium-bearing sphalerite core from the West Desert deposit, photo courtesy of American West Metals Ltd., and* ***(B)*** *reflected-light photomicrograph of indium-rich sphalerite (dark gray) with chalcopyrite inclusions (yellow) from West Desert, photo from Dyer and others (2014).*

up to 9 wt. %, far exceeding indium concentrations measured at other base metal deposits (figure 23). An estimated 3.5 million lbs of indium is present in the deposit. The United States imported approximately 375,000 lbs of indium in 2021, a marked increase over the previous four years, hence the West Desert project contains enough indium to supply the entire current U.S. consumption for about 10 years at current import rates. The deposit has experienced renewed exploration starting in 2022 that will focus on expanding the skarn resource, defining potential porphyry mineralization, and identifying other possible deportations of indium (e.g., chalcopyrite, magnetite).

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Vanadium

Overview and Criticality

Vanadium is a silver-gray transition metal that forms colorful compounds due to its many oxidation states. For example, vanadium minerals are often brightly colored (such as red vanadinite or yellow carnotite), and compounds of vanadium are known in all oxidation states from -1 to +5. Because vanadium is malleable, ductile, and corrosion-resistant, its main uses are in metal alloys, such as high-strength low-alloy steels. The metallurgical applications of vanadium were recognized in the early 1900s, and Henry Ford was one of the first to take advantage of vanadium steel's lightweight strength on an industrial scale. A 1908 advertisement for the Model T exhorted vanadium steel as the "strongest, toughest, and most enduring steel ever manufactured." More recently, vanadium has come into the spotlight for the potential of vanadium redox flow batteries (VRBs), which may play an important role in large-scale energy storage, such as at renewable energy facilities.

No vanadium has been mined in the United States since 2012, the last year that sandstone-hosted uranium-vanadium mines on the Colorado Plateau were active. Byproduct vanadium was recovered from older ores and waste feeds at the White Mesa Mill in San Juan County in 2019 and 2020, yielding high-purity "black flake" vanadium pentoxide (figure 24), but vanadium recovery has since been suspended in favor of a REE recovery circuit. However, should vanadium economics become favorable, White Mesa could shift back to vanadium recovery and would represent a notable boost to project economics for deposits in Utah.The majority of vanadium used in the United States is imported from countries like Brazil, South Africa, Austria, and Canada. Vanadium's criticality is based on the United States' high import reliance, despite the existence of domestic resources, and on the necessity of vanadium for infrastructure development and specialty applications like aerospace titanium alloys, where no substitute exists.

Sources and Geology

Globally, the most common deposit type for vanadium is vanadium-rich titanomagnetite deposits. These deposits form in stratiform tabular bodies of mafic to ultramafic magmas where the vanadium-rich titanomagnetite occurs in layers of either massive or disseminated ore. These layered intrusions were likely formed through settling of a heavier, iron-rich magma phase to the bottom of the magma chamber during crystallization and are often associated with metals such as chromium, copper, nickel, and platinum group metals. Other types of deposits include sandstone and shale-hosted vanadium and vanadate deposits. In Utah, sandstone-hosted uranium and vanadium deposits occur in fluvial sandstone lenses in the Triassic Chinle and Jurassic Morrison Formations, and vanadium is commonly found in the mineral carnotite (figure 25).

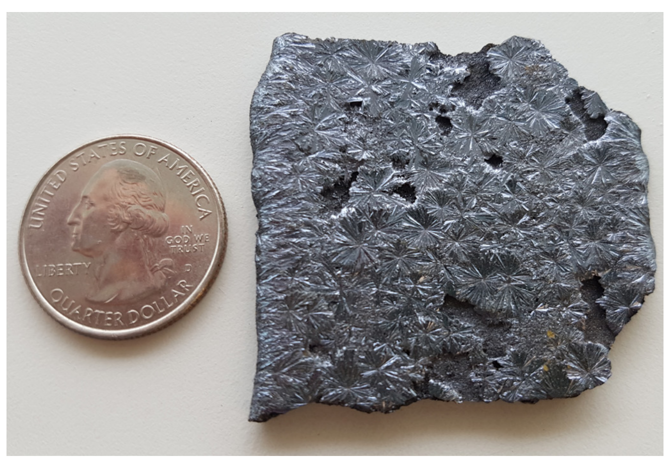

Figure 24. *"Black flake" vanadium pentoxide produced at White Mesa Mill.*

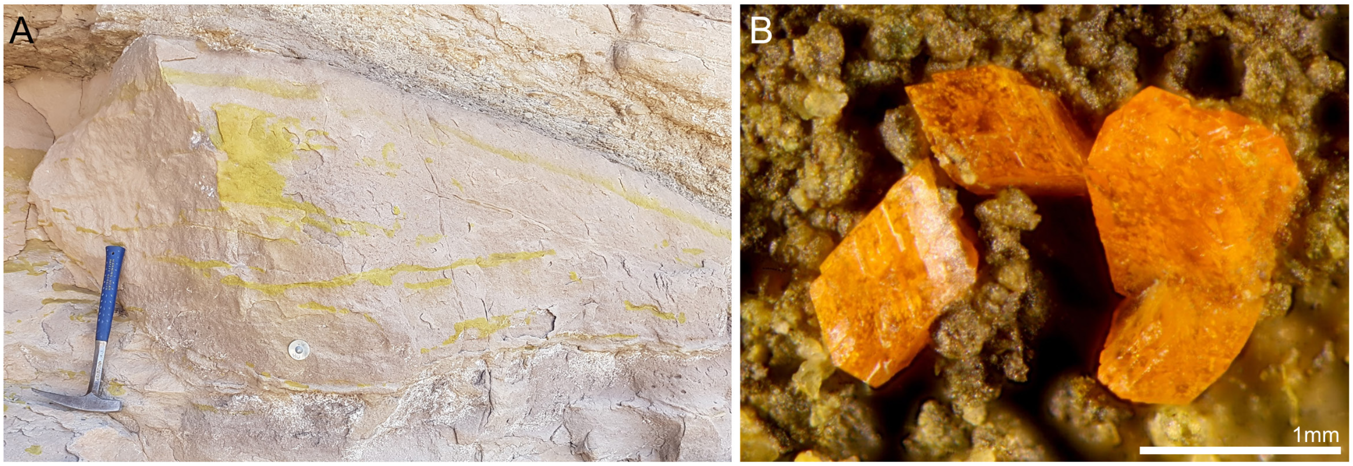

Figure 25. (A) *Yellow carnotite mineralization roughly parallel to bedding in cross-bedded sandstone in the Temple Mountain mining district.* ***(B)*** *Crystals of orange lasalite, a vanadium-bearing mineral. Sample from the Vanadium Queen mine, where the mineral was first identified, in the La Sal mining district, which the mineral was named for. Specimen and photo courtesy of Joe Marty.*

Vanadium in Utah

Utah's Colorado Plateau is home to many sandstone-hosted uranium and vanadium deposits (figure 26). These were originally mined for vanadium prior to the uranium boom in the 1940s and beyond. Although the main mining focus on the Colorado Plateau historically has been for uranium, over 135 million lbs of vanadium pentoxide have been mined in Utah since mining began in the early 1900s. The Colorado Plateau's sandstone-hosted deposits represent the primary domestic source for vanadium in the United States, and Mills and Jordan (2021) estimate over 55 million lbs of vanadium resource remains in Utah, though this is almost certainly underestimated given the historical bias towards uranium exploration.

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Utah Spotlight: Colorado Plateau

The Colorado Plateau is a physiographic and geologic region covering southeastern Utah, northeastern Arizona, northwestern New Mexico, and southwestern Colorado. In Utah, the plateau is home to some of the most scenic state and national parks, such as Canyonlands and Arches. This geologic province has been the main source of domestic uranium mining and led the United States to a position of dominance in the global uranium market from the early 1950s to the late 1970s, starting with the discovery of the Mi Vida uranium mine (figure 27) in Utah's Lisbon Valley mining district in 1952. Utah's Colorado Plateau also contains significant vanadium mineralization as well as lesser copper and cobalt mineralization, all found in sediment-hosted deposit styles (figure 28). The 25-mile-thick crustal block comprising the Colorado Plateau has experienced little deformation in the past 500 million years, in contrast to the strongly folded and extended Basin and Range Province to the west and the highly deformed and uplifted Rocky Mountains to the north and east. The stratigraphy of the Plateau is composed of metamorphosed Precambrian basement overlain by Paleozoic marine units, with a gap of several hundred million years in between. The marine units transition into younger, terrestrial units manifesting as the magnificent cross-bedded red sandstone units that give southern Utah the nickname of "red rock country." The sediment-hosted uranium and vanadium deposits form in sandstone or shale fluvial channels, and uranium mineralization is thought to be associated with Mesozoic groundwater that contained low concentrations of uranium progressively deposited in organic-rich sites (e.g., plant detritus) over long periods of time, eventually forming large deposits. The source of vanadium, which is spatially associated with uranium, is less clear though common theories include dissolution of iron and titanium-oxide minerals or

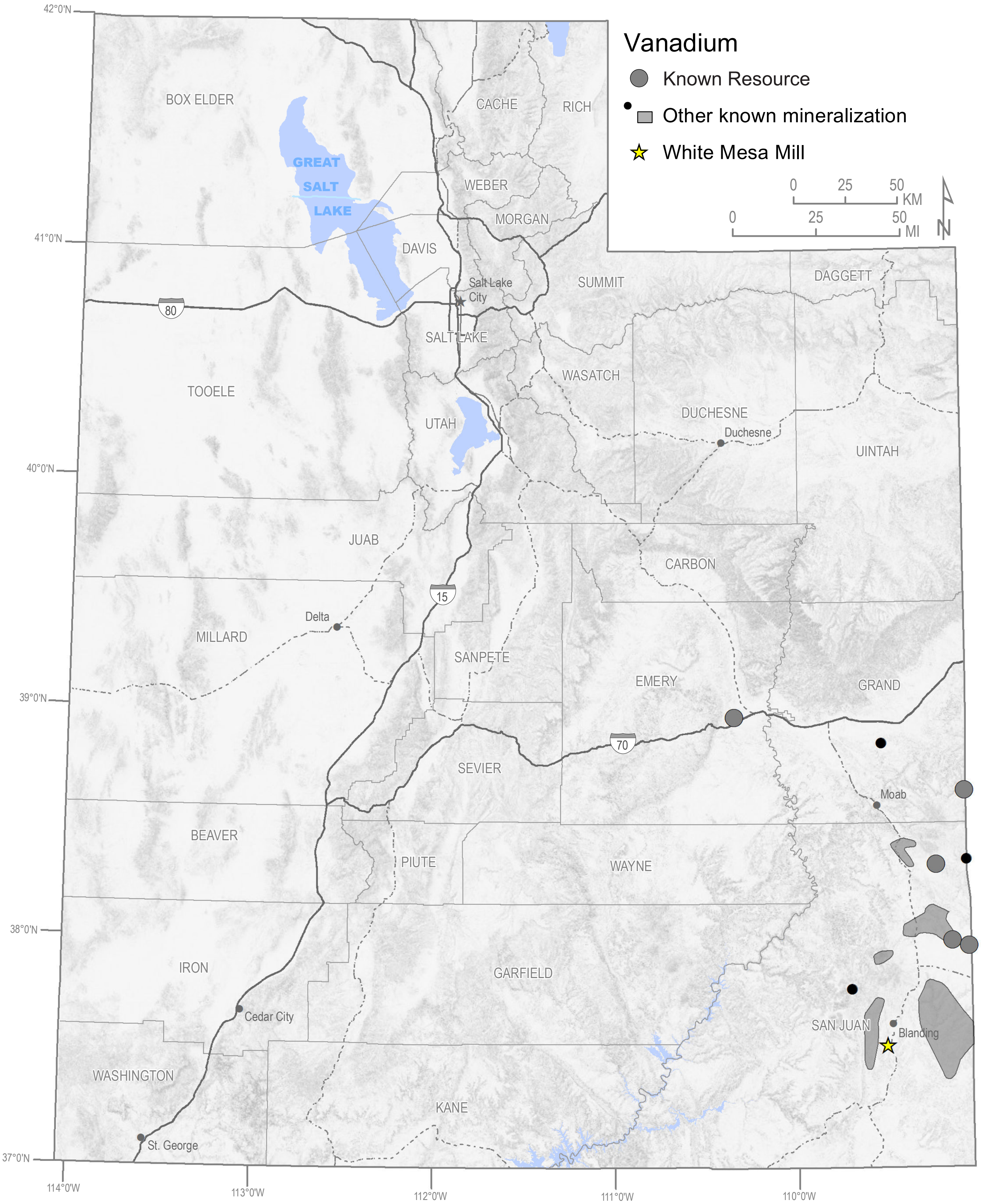

Figure 26. Vanadium resources in Utah.

Figure 27. *Mi Vida uranium mine, discovered by Charlie Steen in 1952.*

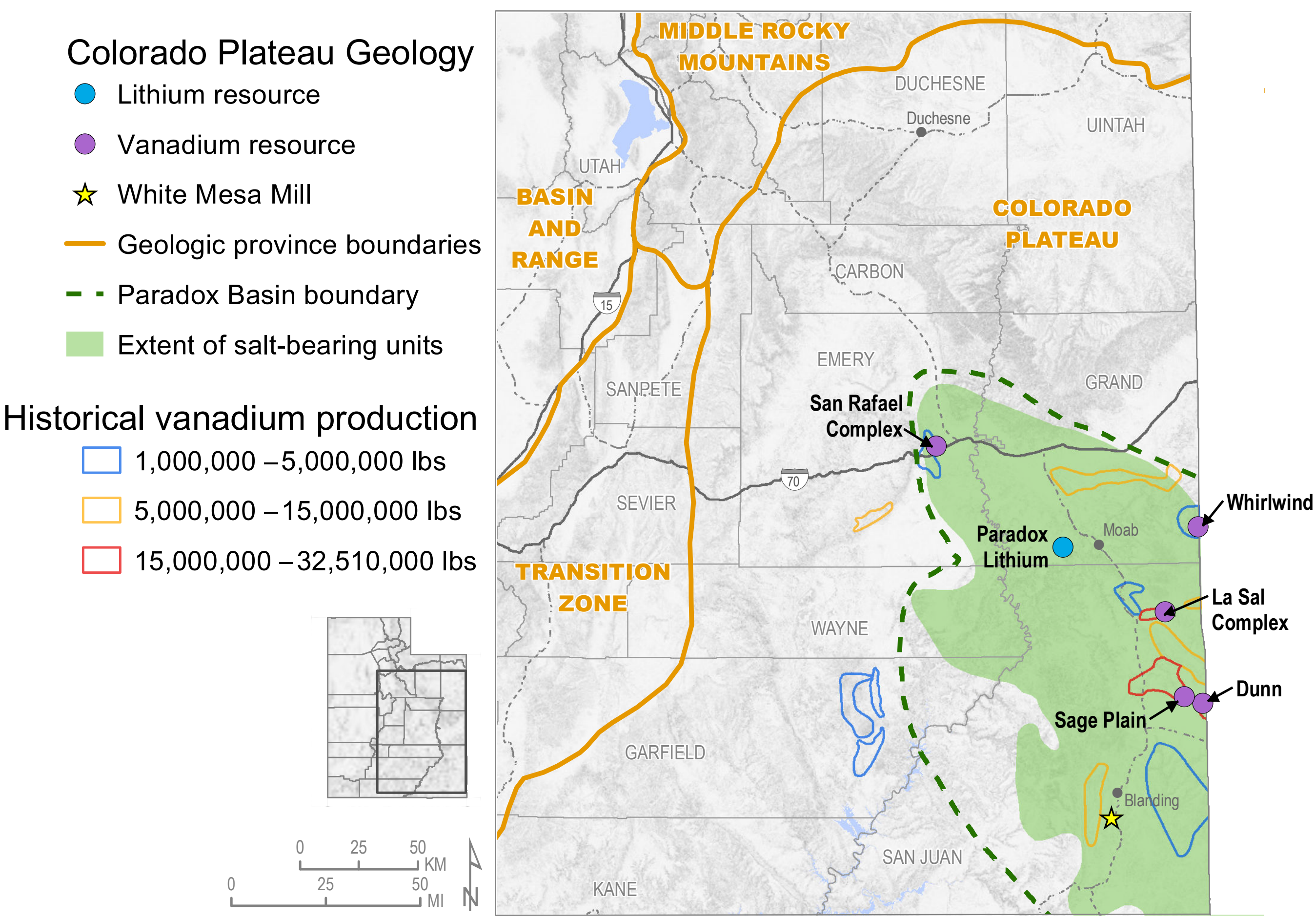

Figure 28. *The Colorado Plateau geologic province in Utah.*

concentration via hydrocarbons. Hydrothermal saline basin brines sourced from Paradox Formation evaporites, or salt-bearing formations (figure 28), scouring metal from the Cutler and Chinle Formations are thought to be the source of the younger (post-Cretaceous) sediment-hosted copper ± cobalt deposits in the region (see Cobalt section).

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Zinc

Overview and Criticality

Zinc is the 24th most abundant element in the earth's crust and the fourth most commonly produced metal globally, following iron, aluminum, and copper. Zinc is most commonly known for its role in providing a coating to protect metals such as iron and steel from corrosion, known as galvanizing, as well as being an important component in many alloys and metallurgical uses. Zinc's use in brass (an alloy of zinc and copper) was known centuries before it was isolated as an individual element, and zinc oxide is a common skin protectant. In the evolving energy landscape, zinc has seen expanded use in both existing technology (e.g., weatherproofing wind turbines) and in new technology (e.g., industrial scale zinc-air batteries). The World Bank estimates zinc is an essential component for wind, solar, hydro, and nuclear energy production as well as energy storage. The United States hosts one of the largest zinc mines in the world, but given how much zinc is used in modern life, the nation is still about 75% import reliant for zinc, on par with other critical minerals like cobalt and barite. The decision to add zinc to the U.S. critical mineral list in 2022 was based on zinc's essential role in basic infrastructure, especially with the recent funding of the Bipartisan Infrastructure Law, and renewable energy buildout.

Sources and Geology

Zinc is mined in five U.S. states, and one of the world's largest zinc mines, the Red Dog mine in Alaska, produces 4% of the world's zinc along with byproduct lead, silver, and germanium. The United States also hosts one domestic primary zinc smelter, meaning that a complete domestic supply chain for zinc exists, even though it is not able to meet current domestic demand. Globally, zinc is produced mostly from three types of deposits: SEDEX and MVT deposits (see Germanium and Gallium section) and volcanogenic massive sulfide (VMS) deposits. SEDEX deposits account for more than 50% of global zinc resources, and MVT deposits have traditionally been a major source of zinc in the United States. VMS deposits are more commonly known as "black smokers" and form from submarine volcanic processes that create seamounts rich in copper, gold, and silver in addition to base metals like zinc and lead.

Zinc in Utah

Utah ranks ninth in the United States for historical zinc production, and zinc is the seventh most valuable metal produced from the state. Historical zinc production was mainly driven by lead, which is a common co-product in many of Utah's major zinc mines. The relationship between lead and zinc, and to a lesser extent silver, is because most zinc in Utah is found in the western part of the state (Basin and Range Province, figure 2) in carbonate replacement deposits, which are typically rich in lead and silver. Carbonate replacement deposits are blanket-like deposits associated with emplacement of magmatic bodies that drive fluids into the surrounding carbonate country rock. Carbonate replacement deposits are a distal expression of porphyry systems, whereas skarn deposits, another source of zinc, are similar but more proximal to the porphyry body. The Bingham and Park City mining districts are the two largest historical zinc producers in Utah, followed by the greater Tintic, Stockton, and Ophir districts, all dominated by carbonate replacement deposits as the source of zinc (figure 29 and 30). Zinc and lead mining decreased substantially in the 1970s, and no zinc is mined in Utah today. Zinc mining was particularly impacted by the decrease in lead use in the late 20th century as the toxic properties of lead meant it was no longer used in mainstream infrastructure applications such as plumbing pipes.

Only two deposits in Utah have modern established resources of zinc, though it is clear from the state's mining history that more potential exists, especially when decoupled from the economics of lead. The Burgin mine, a substantial historical producer of lead in the East Tintic district, is a carbonate replacement deposit and was estimated in 2011 to contain over 100,000 tons of zinc, in addition to silver, gold, and lead. The mine has not been in operation since 1978 when high mining costs and technical challenges such as the inflow of hot saline groundwater ended active mining. After closing, the mine filled with water to the 1100 level, posing a significant challenge to restarting mining operations. The other deposit with an established resource of zinc is the West Desert deposit (see Indium) in western Juab County. West Desert is estimated to contain nearly 1.5 million tons of zinc, which is the primary commodity at the deposit. Unlike most other zinc mining in Utah, West Desert is a skarn deposit and hence does not carry the lead liability found in carbonate replacement deposits.

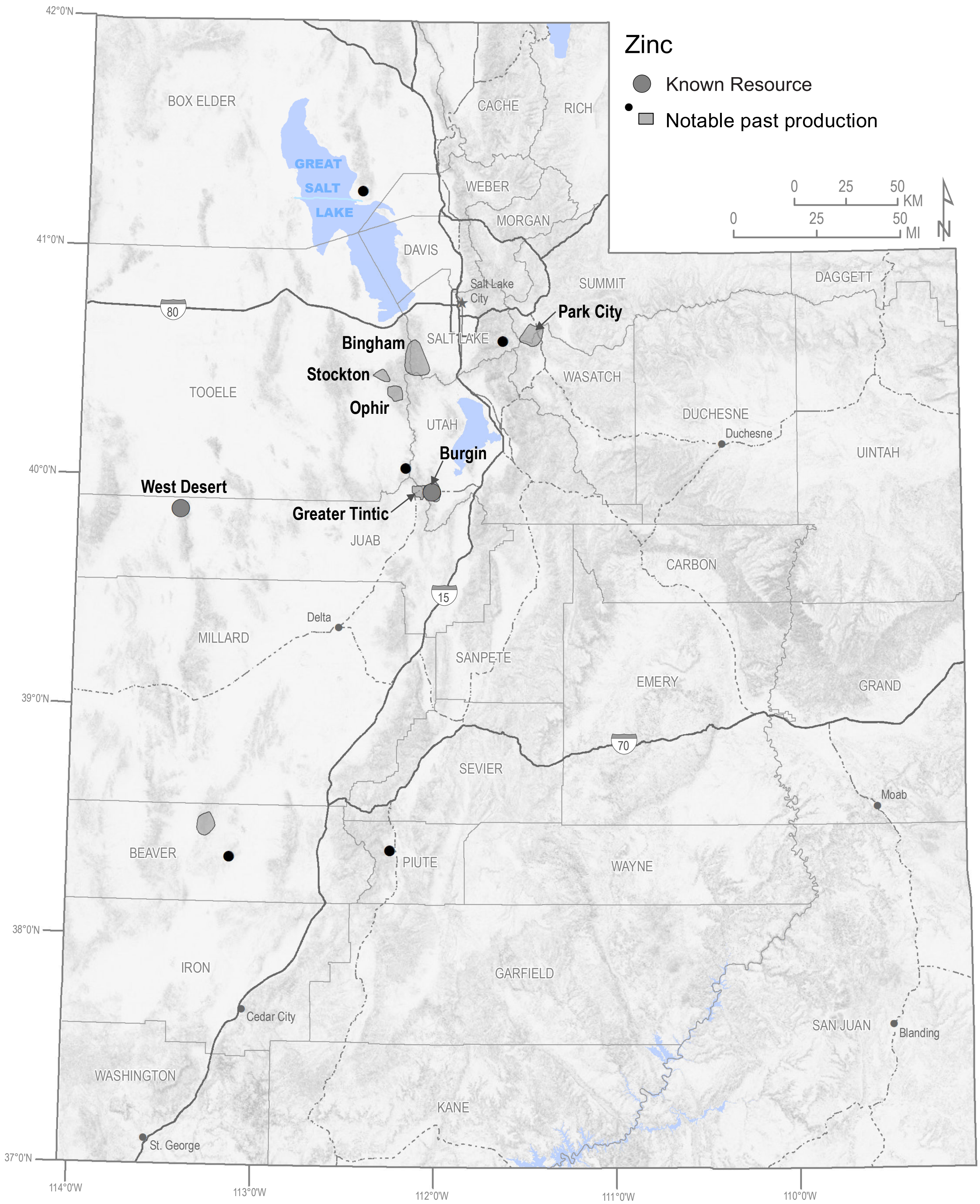

Figure 29. *Zinc mineralization in Utah.*

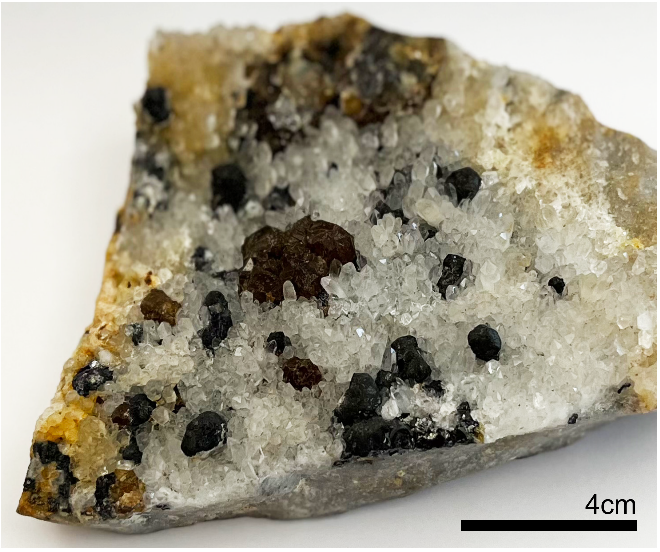

Figure 30. *Sphalerite from the Park City mining district.*

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PAST PRODUCTION (LIMITED POTENTIAL) OF CRITICAL MINERAL RESOURCES IN UTAH

Antimony

Antimony is one of the six commonly recognized metalloids, also known as semi-metals. Like most metalloids, antimony appears metallic in its native form but is brittle and a poor conductor of heat and electricity. However, in metallurgical applications, antimony can add strength, hardness, and corrosion resistance to alloys. The main uses of antimony are as a flame retardant, in metal compounds such as lead-acid batteries, in ammunition and semiconductors, and in non-metal products such as ceramics and glass. Antimony was named as a critical mineral based on a high import reliance and use in military applications (e.g., as a hardener for ball bearings and armor-penetrating bullets, and as a strengthener for cable sheaths and tank linings). The United States does not produce any antimony domestically, importing antimony mainly from China and to a lesser extent from Italy and India. Antimony forms in a variety of deposit types and can be produced as a byproduct, though primary antimony deposits of stibnite (Sb_2S_3, figure 31) associated with orogenic, magmatic-hydrothermal, and sediment-hosted mineralization make up most of the current antimony production globally.

The majority of antimony historically produced in Utah (figure 32) comes from the Antimony district in northwestern Garfield County (also known as the Coyote Canyon district). Production in this district was from hand sorted high-grade stibnite ore and took place in the late 1800s, with intermittent production into the 1960s. The Antimony district deposits are hosted in sandy carbonate units of the Paleocene Flagstaff Formation, and ore occurs as replacement-style lenses and veinlets of stibnite. A roughly estimated 210 million lbs of antimony is judged to remain in the district. Other past producers of antimony include the Lejaiv mine in Washington County (vein and replacement-style stibnite in the Paleocene Claron Formation, possibly associated with sediment-hosted gold at the Goldstrike district), the South Hecla mine in the Cottonwood district (vein and replacement-style silver-lead mineralization with byproduct antimony), and the Dry Lake Antimony mine in Box Elder County (vein-hosted stibnite with associated silver). Antimony is an accessory element in sediment-hosted gold deposits such as Mercury, though there are no records of antimony being produced from these deposits in Utah.

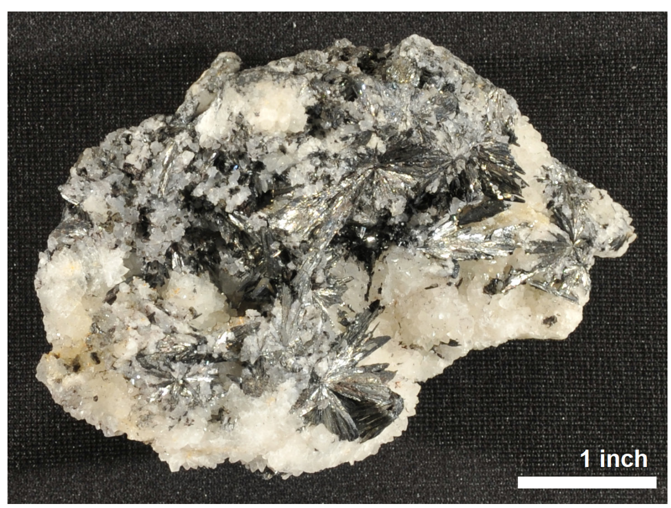

Figure 31. *Stibnite from the Silver King Coalition mine in the Park City mining district.*

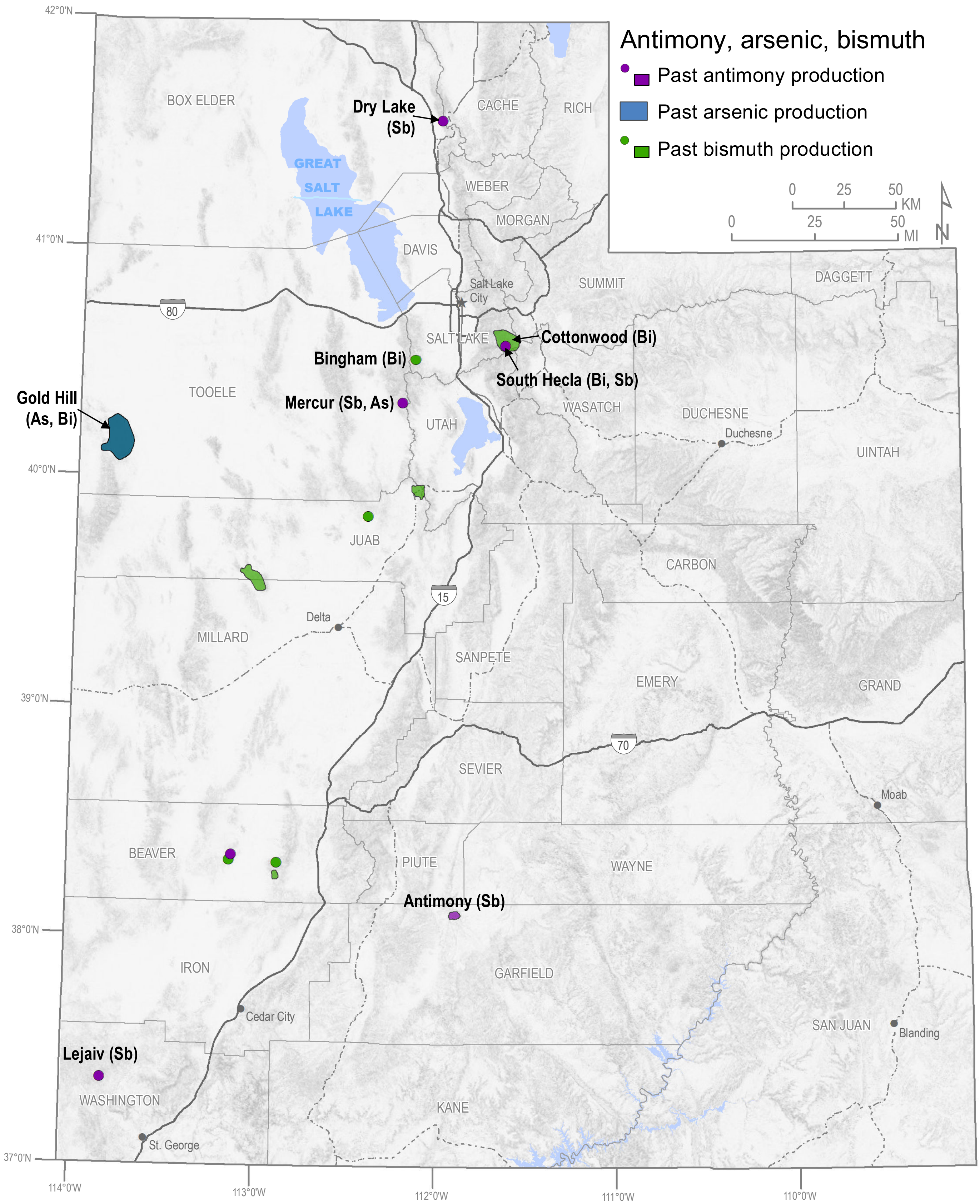

Figure 32. *Antimony, arsenic, and bismuth mineralization in Utah.*

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Arsenic

Like antimony, arsenic is a metalloid and has characteristics of both metals and nonmetals. Many people may associate arsenic most strongly as a poison—after all, it is thought to have been the poison of choice for the Borgias family during the Renaissance period—however, arsenic has many useful applications. Arsenic is used in compounds for semiconductors in solar cells, space research, and telecommunications (gallium arsenide), specialty optical materials (germanium arsenic selenide), and short-wave infrared technology (indium gallium arsenide). The United States has not produced arsenic domestically since 1985 and is reliant on imports from countries like China and Morocco. Arsenic rarely occurs in its native form in nature and its ore minerals include arsenopyrite (FeAsS), realgar (AsS), and orpiment (As_2S_3). Rarely mined as a primary commodity, arsenic is mainly recovered as a byproduct of gold, copper, and other metal mining operations.

In Utah, the Gold Hill district in Tooele County was Utah's premier historical arsenic producer (figure 32). Arsenic was mined from arsenopyrite-bearing polymetallic veins and replacement deposits associated with Jurassic-age magmatism intruding into Paleozoic carbonate basement. Along with the arsenic, other metals such as copper, lead, silver, and gold were also mined from these types of deposits. Arsenic production took place during the 1920s and again during WWII, producing an estimated 24,000 tons of arsenic metal, nearly three times the modern annual consumption of arsenic. Other sources of arsenic in Utah include sediment-hosted gold deposits, such as in the Mercur district, where orpiment and realgar are commonly associated with gold mineralization (figure 33). There is no record of arsenic production from any of Utah's major sediment-hosted gold districts; however, this may be because arsenic was viewed as a less valuable byproduct and therefore production was not closely monitored.

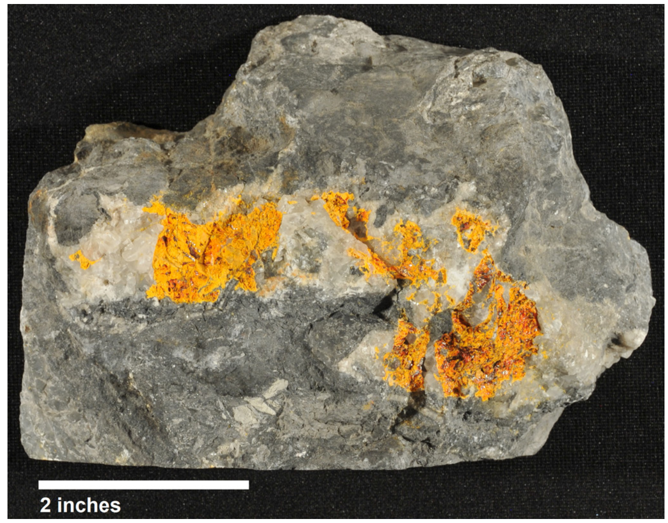

Figure 33. *Realgar (red) and orpiment (orange) from the Mercur mine.*

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Barite

Barite is a barium sulfate mineral ($BaSO_4$) that is useful because of its high density and inertness. Those characteristics make it ideal for use as a weighting agent in drilling fluids for oil and gas wells, which accounts for the vast majority of its sales in the United States. Barite has several other uses such as in medical applications and as a filler, extender, or weighting material in a variety of products. In 2021, the United States imported more than 75% of the barite it consumed, providing justification for its criticality. Globally, China is the leading producer and supplied about 41% of the United States' imported barite in 2021. Several countries, including Iran, Kazakhstan, and India, have significant reserves. Economically important deposit types for barite include bedded, vein (also known as filling or replacement), and residual deposits. Bedded deposits account for most of the production and reserves globally. In the United States, barite production currently comes from bedded deposits in Nevada.

Utah has produced a small amount of barite in Juab, Beaver, and Emery Counties (figures 34 and 35), but most of the production was from several decades ago, primarily the late 1950s and early 1960s. The largest historical producer,

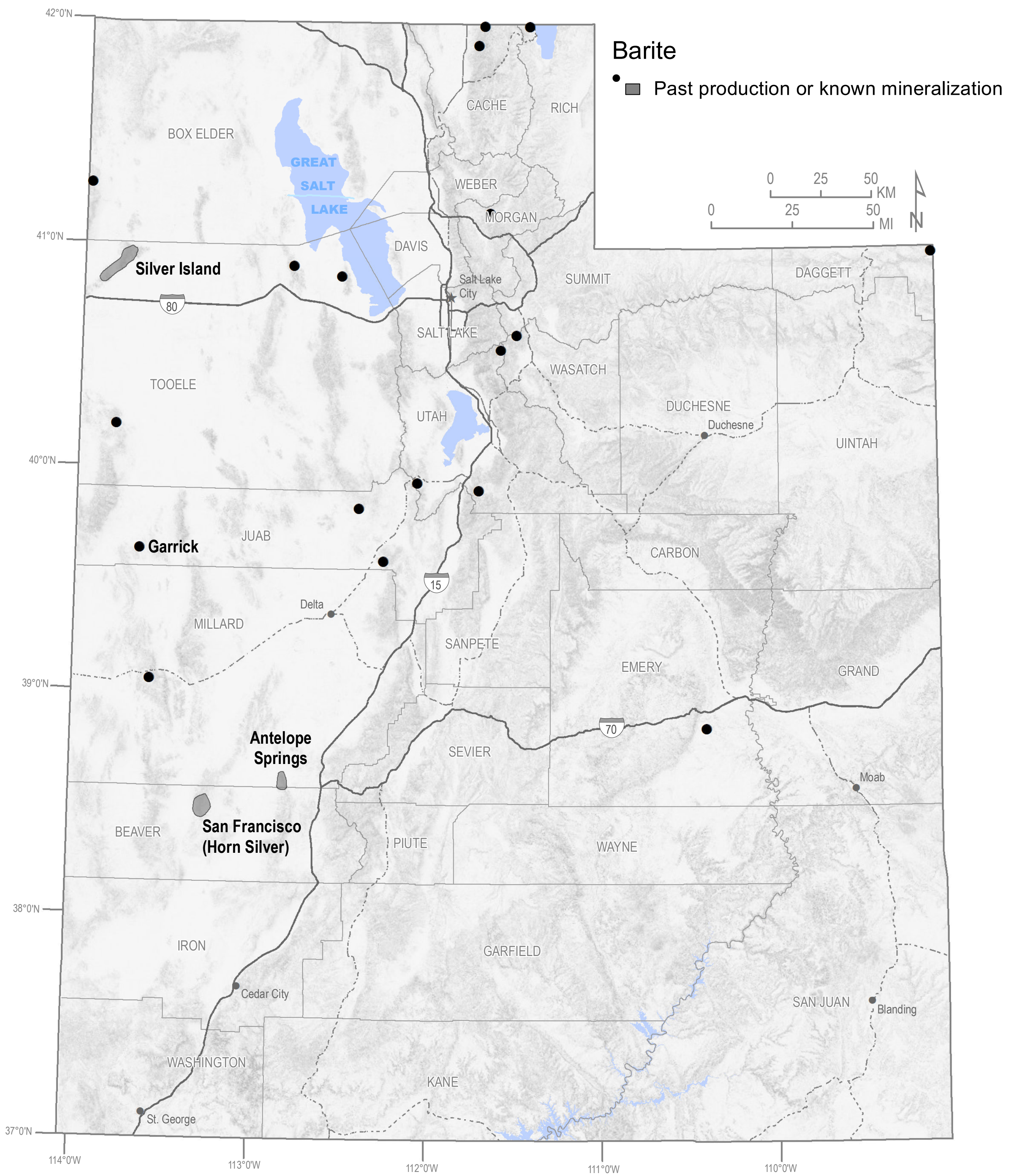

Figure 34. *Barite mineralization in Utah.*

the Garrick mine, is a vein deposit in western Juab County. Most of the remaining production came from the Horn Silver mine in Beaver County (as a byproduct) and the Barium, Inc. mine at an unknown location in Emery County. A small barite mine in Tooele County attempted to produce in the early 2000s, but records are unclear as to whether any material was mined. Several small deposits, occurrences, and prospects exist across Utah, but none of the known deposits are significant enough to be considered economic under current conditions.

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Figure 35. *Barite from the Buckhorn mine.*

Bismuth

Bismuth is a post-transition metal that is softer and less conductive than its metal cousins. Bismuth has the strongest diamagnetism of any metal, meaning it is repelled instead of attracted by a magnetic field, and it has a relatively low melting point, leading to its use in fusible alloys. Brittle and crystalline in its native form, bismuth's most recognizable application is as the main ingredient in the stomach medicine Pepto-Bismol®. Bismuth's lack of toxicity makes it applicable in medicine and as a non-toxic alternative to lead, such as in plumbing and bullets. The United States is highly import dependent for bismuth, and the majority of imports come from China. Bismuth is a byproduct associated with base and precious metal deposits, such as copper porphyries and lead-zinc replacement deposits.

Bismuth has historically been mined in Utah from deposits in the Cottonwood, Gold Hill, Lincoln, and Drum Mountain districts and has been produced as a byproduct of mining in the Tintic district, all generally before the 1960s (figure 32). The South Hecla mine in the Little Cottonwood district was one of the leading bismuth producers in the United States in the first half of the 1900s and remains the largest historical producer of bismuth in Utah. Bismuthinite (Bi_2S_3, figure 36) in the South Hecla mine was hosted with lead, zinc, silver, copper, and gold ore minerals in replacement deposits developed around the Alta intrusive stock in the Mississippian Fitchville and Humbug Formations. Bismuth is also present at Bingham Canyon (figure 15), where it is considered a deleterious element in the copper refining process. Bismuth causes grain boundary cracks when copper is drawn into wires, hence there is significant focus on removing any bismuth impurities from the final copper cathode product. Currently bismuth is discharged with waste water to be treated before going to the tailings impound. However, should bismuth economics improve, bismuth could be recovered as a byproduct of copper and precious metals refining.

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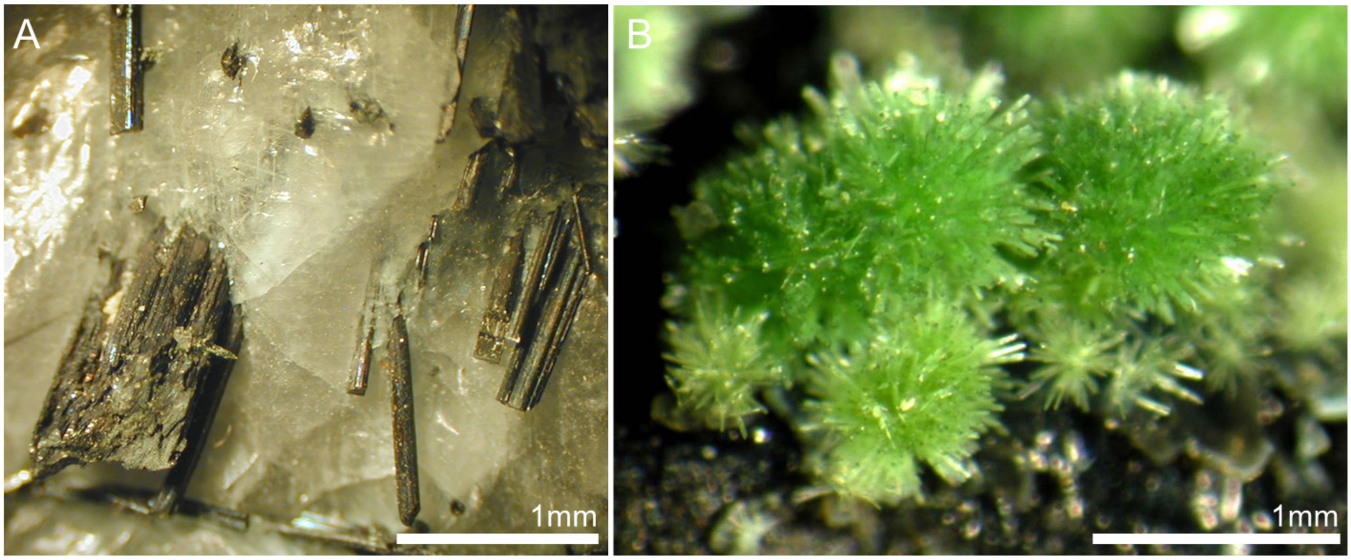

***Figure 36. (A)** Bismuthinite crystals hosted in calcite from the Creole mine in the Lincoln mining district. Specimen and photo courtesy of Dave W. Richardson. **(B)** Green mixite, a bismuth-bearing mineral, from the Gold Hill mining district. Specimen and photo courtesy of Joe Marty.*

Manganese

Manganese is a transition metal, silvery metallic in luster but hard and brittle. Given that manganese is one of the most common elements (12th most abundant crustal element, 5th most abundant metal), surprisingly it does not occur on its own in nature. Rather, it commonly occurs as oxides (e.g., pyrolusite, MnO_2, the main ore mineral for manganese) or with iron minerals. As with other transition metals like vanadium, manganese compounds can be brightly colored. Pink rhodochrosite is manganese carbonate, and the purple color in amethyst is due to manganese impurities in quartz. Manganese is essential to iron-ore refining and for producing steel alloys. Despite the foundational role manganese plays in modern infrastructure, the United States does not produce any manganese domestically. Imports are dominantly from South Africa and Gabon, and to a lesser extent Australia. Despite known resources in the United States, the higher grade and larger size of deposits in other countries make it difficult for domestic operations to compete economically.

Utah was a significant producer of manganese during the first half of the 1900s, most notably from the Drum Mountain district in Juab and Millard Counties (figure 37). The Drum Mountain district is centered around a low-grade Eocene-age porphyry with adjoining copper, gold, and silver carbonate replacement deposits. However, the significant mine production originally came from sediment-hosted gold mineralization to the south of the porphyry and later from the manganese replacement deposits to the north, both of which are presumed to be related to distal fluid flow associated with porphyry emplacement. The majority of manganese mineralization in Utah is associated with replacement deposits (figure 38), and a number of districts have minor manganese production from replacement deposits in the eastern Basin and Range Province. However, the Little Grand district in the Colorado Plateau region was a notable manganese producer from sediment-hosted deposits. Manganese mineralization in these deposits occurs in limestone and sandstone, similar to the uranium, vanadium, and copper mineralization found in the Colorado Plateau, though the manganese is hosted in the Jurassic Summerville Formation, stratigraphically above the main uranium-vanadium horizons.

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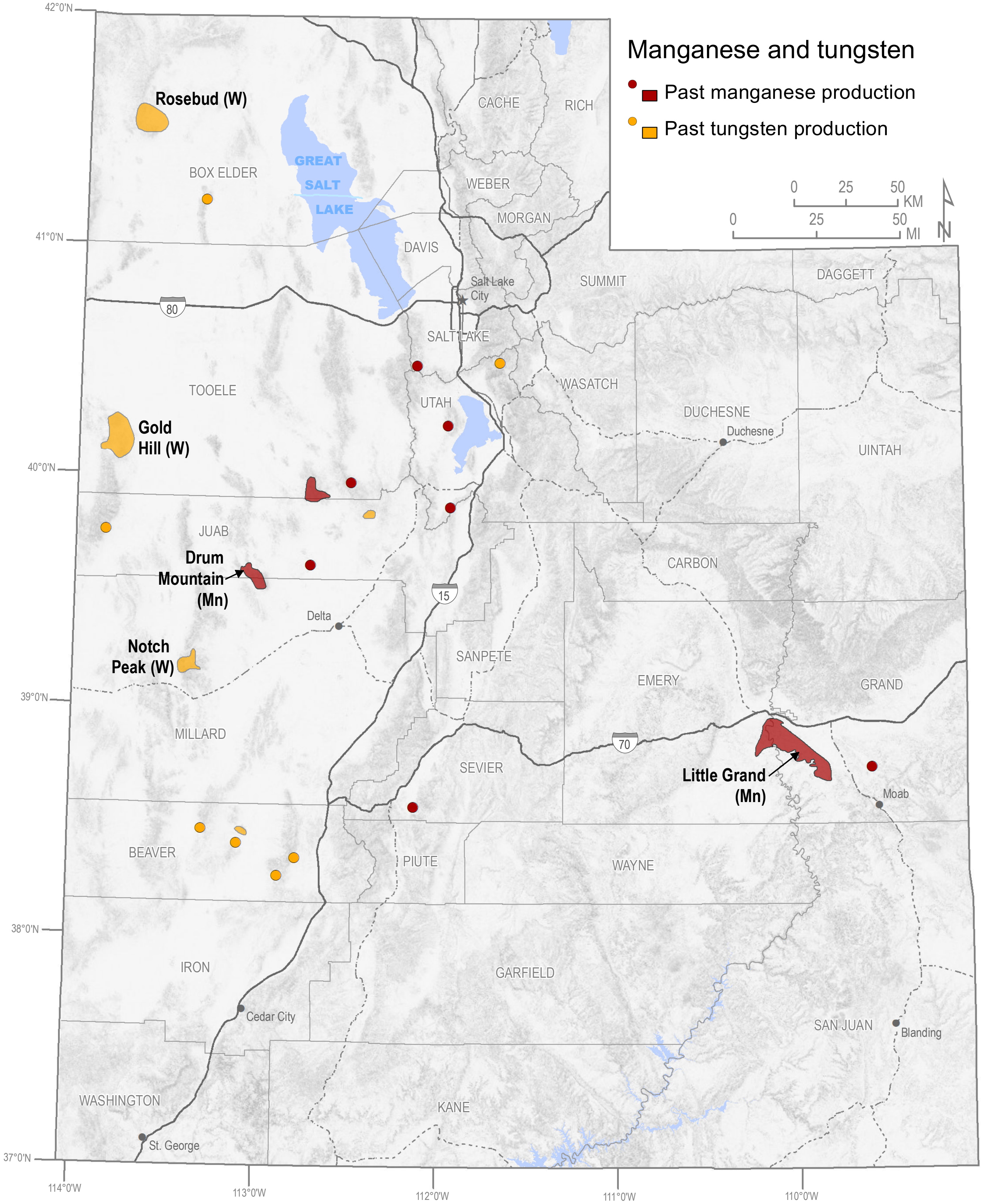

Figure 37. Manganese and tungsten mineralization in Utah.

Figure 38. Replacement-style manganese mineralization from the Long Ridge mining district.

Tungsten

Tungsten is a dense metal with the second highest melting point of any element after carbon. Tungsten is also extremely hard and durable. Once most widely used as the filament in incandescent light bulbs, over 60% of tungsten consumption in the United States is now for tungsten carbide. Only slightly softer than diamond, tungsten carbide is used for products that need to withstand high temperatures and stress such as industrial machinery, cutting and drilling tools, and armor-piercing ammunition. In addition to its use in tungsten carbide, tungsten is also used in various alloys and electrical components. The main ore minerals for tungsten are scheelite ($CaWO_4$) and wolframite ($FeWO_4$). Tungsten deposits are almost exclusively associated with felsic intrusives, and tungsten mineralization can result from contact metasomatism (skarn, greisen, vein, breccia deposits) or can be native to the intrusive itself (tin-tungsten porphyry, pegmatite, vein deposits). The United States does not currently produce any tungsten and imports it from a variety of countries, most notably China, Bolivia, and Germany.

Utah hosts the most recently productive tungsten mine in the United States, the Fraction mine in the Gold Hill district in southwestern Tooele County (figures 37 and 39). In 2016, small-scale mining of skarn and vein-hosted scheelite reported production of 275 tons of ore at a roughly estimated 1.7% WO_3, representing less than 1% of imported tungsten that same year. The mine has not been in operation since. Tungsten mineralization at Gold Hill is associated with skarn and breccia bodies around Jurassic and Eocene intrusions in the Paleozoic carbonate basement. In the Gold Hill and other tungsten districts in Utah such as Notch Peak and Rosebud, the majority of tungsten production was during WWII.

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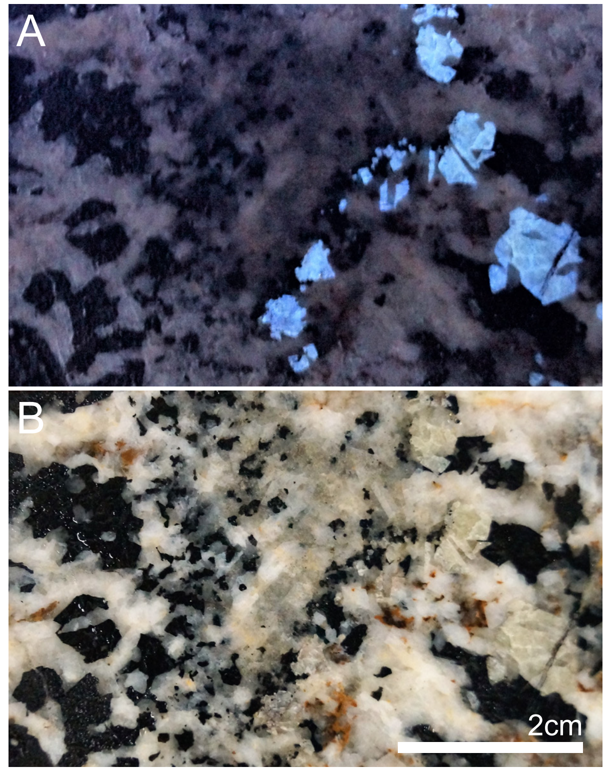

Figure 39. Shortwave ultraviolet light (A) and plain light (B) showing fluorescent scheelite crystals in granodiorite from the Gold Hill mining district (modified from Carey, 2022).

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CRITICAL MINERAL OCCURRENCES IN UTAH

Cobalt

Cobalt shares characteristics with many other critical minerals in the metals family, including durable alloys, low conductivity, high melting point, and multiple oxidation states. Cobalt is best recognized for the striking blue color it produces in glass. Almost half of all cobalt consumed in the United States is for superalloys used primarily in jet aircraft engines. Additional uses include wear-resistant tool components, metallurgical alloys, and a wide variety of chemical applications. Globally, the most common use of cobalt is in cathodes of rechargeable batteries for electric vehicles. Cobalt is produced as a byproduct of copper and nickel mining from sediment-hosted copper (Congo and Zambia), nickel laterite (Australia and Cuba), or magmatic sulfide deposits (Australia and Canada). The United States has minor cobalt reserves associated with nickel-copper deposits in Minnesota and with polymetallic veins in Idaho. Utah cobalt occurrences are found in sediment-hosted copper and/or uranium deposits of the Colorado Plateau (figure 40), where cobalt

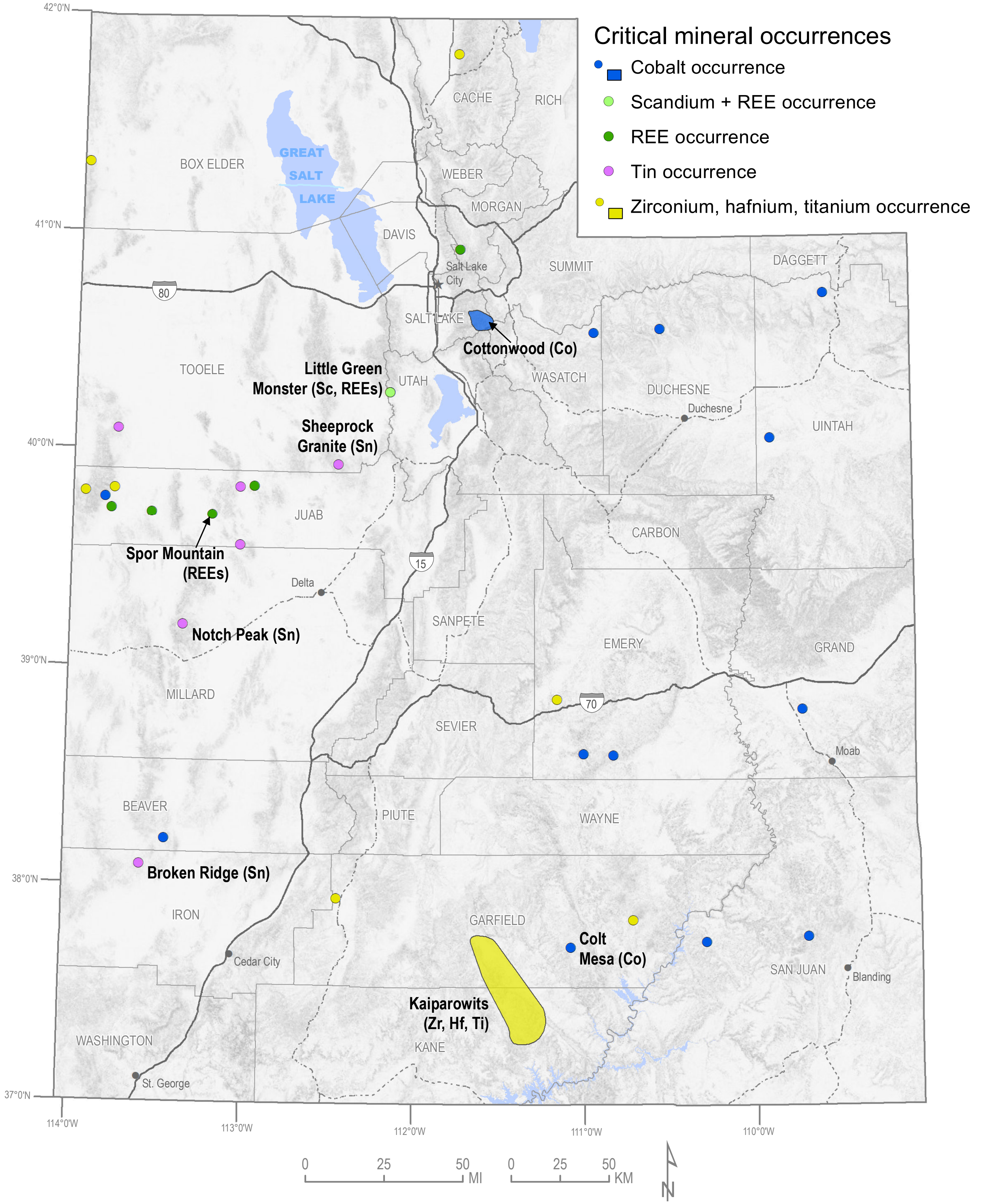

Figure 40. Cobalt, REE, scandium, tin, titanium, and zirconium/hafnium occurrences in Utah.

can occur in values up to a few weight percent. The Colt Mesa deposit in Garfield County was evaluated for cobalt potential in the late 2010s, and sediment-hosted copper projects throughout the Colorado Plateau are considering cobalt as a supporting commodity for project economics. Other minor occurrences include polymetallic veins in base metal districts (e.g., Cottonwood district). Primary cobalt production in Utah is unlikely, but cobalt could potentially be a byproduct of sediment-hosted copper mining from the Colorado Plateau.

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Rare Earth Elements and Scandium

Rare earth elements, more commonly known as REEs, are a broad set of 17chemically and geologically similar elements. REEs include all 15 elements in the lanthanide series on the periodic table, as well as scandium and yttrium, though the inclusion of scandium is sometimes debated. Despite implications of the name, REEs are not actually rare in terms of crustal abundance; they do, however, rarely form concentrated deposits that can be economically mined. REEs have a wide range of defense, energy, and industrial applications, such as magnets, catalysts, and polishing or additives for glass. China is the dominant global producer of rare earths, largely from a unique carbonatite mine known as the Bayan Obo deposit. Prior to 2011, China controlled over 90% of the global rare earth market. However, concerns over supply stability have caused other countries to seek to develop alternative REE sources. In the United States, REEs are mined from the Mountain Pass deposit in southeastern California and from heavy mineral sands in the southeastern U.S. The United States is developing domestic REE processing ability, including at the White Mesa Mill in San Juan County, but currently most REE ores are sent overseas for refining. Given the current domestic import reliance, the risk of supply disruption, and the widespread and specialty uses of REEs, they are considered highly critical.

With the exception of scandium, rare earths have never been produced in Utah and there are no known primary rare earth deposits, though minor prospects have been identified (figure 40). Small amounts of scandium were produced from the Little Green Monster variscite deposit near the Lake Mountains in Utah County, where variscite ($AlPO_4 \cdot 2H_2O$, figure 41) and

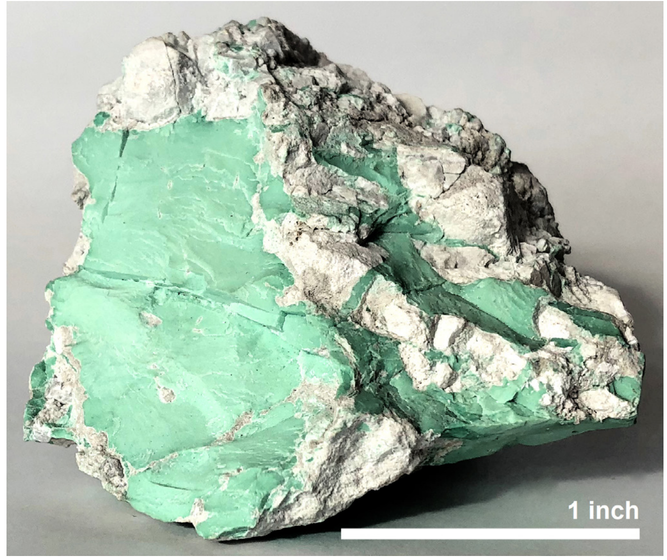

Figure 41. *Variscite from the Little Green Monster/Clay Canyon deposit.*

crandallite ($CaAl_3[PO_4]_2[OH]_5H_2O$) contained 0.01 to 0.8 wt. % scandium oxide (Sc_2O_3). Volcanic units in the Beryllium Belt (figure 5) have evolved chemistries that may favor rare earth enrichment, and limited geochemical work has shown that the Spor Mountain beryllium tailings may be enriched in REEs as a byproduct. Other potential sources of REEs in Utah include heavy mineral deposits, phosphate deposits, and iron apatite deposits, but there has been little research on the potential of those deposits.

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Tin

Tin, which takes its element symbol Sn from the Latin name stannum, has a history dating back more than 5000 years to when it was fundamental to the onset of the Bronze Age. Bronze, an alloy of tin and copper, was harder than other known metals or alloys, and its discovery (as early as 3500 B.C.) drove the development of more advanced tools. Another significant and more modern use of tin is the tin can, which allowed preservation and transport of food, but this application has been largely replaced in modern times by aluminum. Currently tin is a diverse metal used in a variety of applications including tinplate for steel containers, construction materials, alloys and solder, and chemical uses such as indium-tin-oxide (ITO), a clear conductive film on smartphones and touchscreens. The United States does not mine or smelt tin, but imports refined tin from countries like Indonesia, Malaysia, and Peru, and scrap tin from Canada. Tin is often mined from placer deposits of the main ore mineral, cassiterite (SnO_2), which is dense and sinks to the bottom of streambeds. Primary tin deposits are associated with high silica and aluminum granites, and mineralization can occur in greisenitic zones, disseminated ore, sheeted veins, or skarns. Utah has no significant tin deposits; however, small occurrences are known in areas with silicic peraluminous intrusions such as Broken Ridge, Notch Peak, and the Sheeprock Granite (figure 40). Tin production is unlikely in the near future, as these deposits are low grade, but combined metal contents (molybdenum, tungsten, tin, etc.) of some prospects may eventually make byproduct tin production economic.

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Titanium, Zirconium, and Hafnium

Titanium, zirconium, and hafnium are transition metals that have several uses. Most titanium is used as pigment in paints, but it is also important for aerospace components, turbine engines, medical applications, and other uses. Key characteristics of titanium include corrosion resistance and high strength at a relatively light weight. Zircon, an important zirconium silicate mineral, has a variety of uses including in ceramics, foundry sand, opacifiers, and refractories. Significantly, both zirconium and hafnium metal are used in nuclear reactors and in chemical industries. Hafnium is also important for superalloys used in jet engines and turbine engines. Most of the titanium mineral concentrates consumed in the United States that are used to produce various titanium products are imported (around 90%). The United States is an exporter of zirconium ores and concentrates; however, zirconium metal production is susceptible to disruption due to a single point of supply chain failure domestically. These critical minerals are grouped together because they are most often extracted from the same type of deposit, i.e., heavy mineral sands, though other deposit types also have some significance. Heavy mineral sand deposits are considered placer deposits and form in coastal or alluvial environments where certain dense minerals concentrate due to gravity separation as a result of sedimentary processes. Several countries are important producers of titanium mineral concentrates including China, South Africa, and Mozambique, but China and Australia hold the largest reserves. For zirconium mineral concentrate production and reserves, Australia and South Africa are the most significant countries. Hafnium is a byproduct of zirconium production, because the most important ore mineral for zirconium, zircon, contains small amounts of hafnium. Domestic production of both titanium and zirconium mineral concentrates comes from deposits in Georgia and Florida.

Utah has no history of producing titanium, zirconium, or hafnium. Most of Utah's occurrences of titanium and zirconium are heavy mineral sand deposits, but their small sizes leave little potential for future production. The most significant deposits in Utah are several paleoplacers in the Kaiparowits district in Kane and Garfield Counties (figure 40). These deposits were discovered in the 1950s and have been staked, evaluated, and abandoned multiple times. Within the district, the Mann (Longshot) deposit in Kane County has an inferred resource of 300,000 tons at an average grade of 9.6% TiO_2, 3% ZrO_2, and minor hafnium. The deposit grade is good compared to an average deposit model at 2.5% TiO_2 and 0.9% ZrO_2, but the size is quite small compared to an average deposit size of nearly 100 million tons. The Escalante (Calf Canyon) deposit is not as well defined, but is thought to be larger (perhaps 300,000 to 600,000 tons) at a slightly better grade.

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CRITICAL MINERALS WITH NO KNOWN POTENTIAL IN UTAH

Cesium and Rubidium, Chromium, Graphite, Nickel, Niobium and Tantalum, Other PGEs

Although Utah is a state with a rich and varied mining history and diverse geology, there are certain commodities that Utah is not known to host. These commodities are associated with certain geologic settings, such as magmatic sulfide deposits or carbonatites, that do not exist in the state.

Cesium, used in oil and gas drilling, and rubidium, used in night-vision devices, can often be used interchangeably due to the similarity in their physical properties and atomic radii. They are both found in the mineral pollucite ($[Cs,Na]_2Al_2Si_4O_{12} \cdot 2H_2O$). Pollucite is a hydrous sodium-cesium aluminosilicate mineral that is found in association with lithium-bearing pegmatites. Rubidium can substitute into pollucite for cesium, so it is considered a viable ore mineral for both elements. Rubidium can also be hosted in the mineral lepidolite ($K[Li,Al,Rb]_2[Al,Si]_4O_{10}[F,OH]_2$), a lavender colored lithium-mica also associated with lithium pegmatites. Utah hosts many types of pegmatite, such as beryllium-rich varieties in the Spor Mountain district, but there are no known lithium pegmatites or occurrences of pollucite or lepidolite. In the mid-1960s, the Honeycomb Hills district in western Juab County was reported to have weakly enriched cesium and rubidium in a Pliocene tuff; however, this is unlikely to be of any economic value.

Chromium, more commonly referred to as chrome, is an essential industrial metal most recognizably associated with stainless steel, which contains about 18% chromium. Chromium's hardness, resistance to corrosion, high melting point, and ability to take a high polish are all valuable characteristics for stainless steel and other metallurgical applications (e.g., superalloys). Chromium is primarily produced from the mineral chromite, which is found in layered ultramafic intrusives such as the Bushveld complex in South Africa and in chunks of mafic seafloor thrust onto continental crust called ophiolites. The United States imports chromite almost exclusively from South Africa, and has no current chromium production. The United States' main chromium resources are hosted in the Stillwater Complex, a layered mafic intrusion in Montana that also hosts PGEs, nickel, and copper, though there has been no recent production of chromium from the deposit. Utah does not have any layered mafic or ultramafic intrusions and therefore has no known potential to host chromium deposits.

Carbon is a common constituent in many inorganic and organic materials, but pure carbon in the form of graphite is rarely found in concentrated economic deposits. Graphite is useful for being chemically inert, having high lubricity, and high electrical conductivity. It is mainly used in industrial and metallurgical applications. Graphite deposits occur in metamorphosed carbonaceous sedimentary rocks. For example, most amorphous graphite is sourced from thermally metamorphosed coal. Synthetic graphite can be produced by thermal treatment of hydrocarbons and this is the most common form used in the United States, despite it being more expensive. Utah's Basin and Range Province hosts thick sequences of carbonate rocks that have experienced metamorphism, and the Colorado Plateau hosts numerous coal deposits or units with considerable carbonaceous content (figure 42), but there are no known occurrences of significant graphite development.

Nickel is a relatively common transition metal that is used mainly in steel and other alloys, but also in catalysts and plating. Currently, there is only minor demand for nickel as a constituent of lithium-ion batteries used in electric vehicles, but that demand is expected to increase substantially in coming years. Nickel is mined in the United States from one deposit in Michigan, and as a byproduct of waste processing and smelting from other operations. Primary nickel deposits form as either nickel laterites, which result from near-surface weathering of ultramafic rocks, or from magmatic sulfide deposits, which result from bodies of mafic to ultramafic magmas that have become saturated with sulfur and produced an immiscible metal-rich sulfide liquid. Neither laterite or magmatic sulfide deposits are known to occur in Utah.

Niobium and tantalum, which are almost always found together in nature, are generally associated with alkali-rich intrusives, certain types of pegmatites, and carbonatites. Niobium is important for high-strength steel for defense and infrastructure, and tantalum is used for capacitors in

__Figure 42.__ Carbon-rich layer in the lower Green River Formation. Photo courtesy of Ryan Gall.

cell phones and in superalloys for jet engines. Although Utah hosts some alkaline intrusives and pegmatites, no niobium or tantalum minerals have been detected. Utah has no known carbonatite occurrences.

Although Utah produces minor platinum and palladium as byproducts from Bingham Canyon, the other PGEs rhodium, ruthenium, iridium, and osmium are not present in economic concentrations. However, they share the resistance to wear, tarnish, corrosion, and high temperatures, making them valuable in many industrial applications such as in chemical and glass manufacturing, electronics, and medical implants. Like nickel, the primary source of PGEs globally is from magmatic sulfide deposits. These deposits are associated with large igneous provinces (LIPs), which are not known to exist in Utah.

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