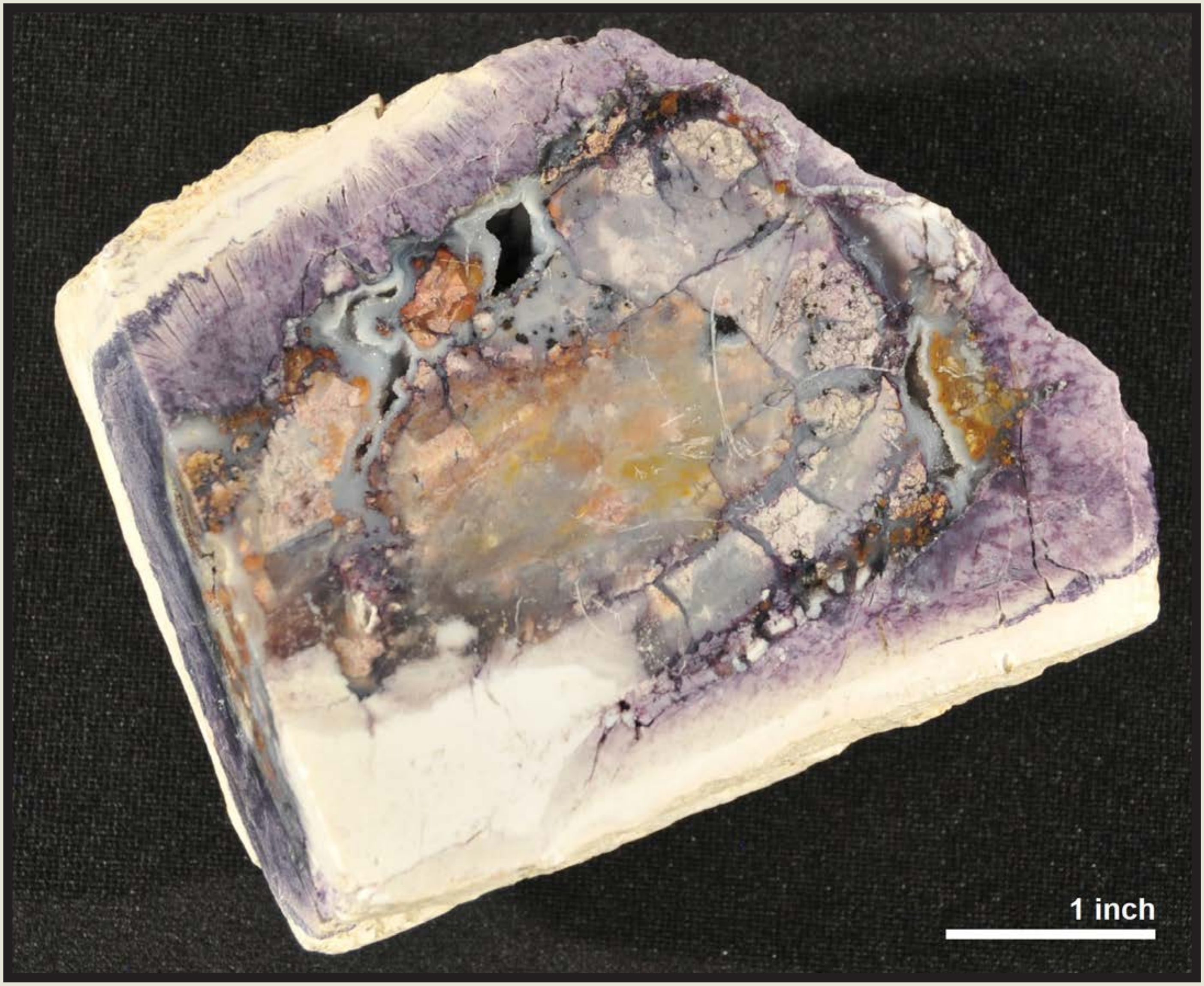
CRITICAL MINERALS OF UTAH

by Stephanie E. Mills and Andrew Rupke



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UTAH GEOLOGICAL SURVEY
UTAH DEPARTMENT OF NATURAL RESOURCES
2020

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Cover photo: *Bertrandite (beryllium ore) and fluorite mineralization from the Spor Mountain mine. Sample courtesy of Mark Milligan.*

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CRITICAL MINERALS OF UTAH

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UTAH'S CRITICAL MINERALS 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 minerals currently in production, defined resources, exploration projects, and potential prospects. This report summarizes Utah's critical minerals and their geographic and geologic distribution within the state. Utah is notable for being the global leader in beryllium production; being the only domestic producer of magnesium metal; being one of two states producing potash and the only domestic producer of high-value potash; being a byproduct producer of platinum, palladium, and rhenium from the world-class Bingham Canyon copper-molybdenum mine; and being a helium producer from natural gas streams. Utah has known resources of aluminum, fluorspar, indium, lithium, uranium, and vanadium, and has previously produced arsenic, antimony, barite, germanium, gallium, manganese, tellurium, and tungsten. Rare earth elements (REEs) could be a potential byproduct of beryllium mine tailings. In total, Utah hosts 28 of the 35 current critical minerals.

Highlights of Utah's critical minerals include:

- **Global leader of beryllium:** The Spor Mountain mine in central Juab County is the largest global beryllium producer, and the yet-to-be-mined bertrandite ore still contained in the deposit is enough to continue mining at current rates for another 75 years.
- **Domestic leader of magnesium metal, lithium byproduct potential:** Utah is the only domestic producer of magnesium metal from a primary source (Great Salt Lake brines) and the operator may soon produce lithium as a byproduct.
- **Domestic leader of high-value potash:** Utah is the only domestic producer of high-value potash as potassium sulfate sourced from Great Salt Lake brine, and one of two domestic producers of the more common potash, potassium chloride, sourced from Bonneville Salt Flat brines and subsurface evaporites near Moab.
- **Bingham Canyon byproduct platinum, palladium, and rhenium:** The world-class Bingham Canyon mine, central to the most historically productive mining district in the United States, produces byproduct platinum, palladium, and rhenium as part of the mining and refining operations.
- **New production of helium:** The Lisbon Valley gas plant in San Juan County began purifying helium from natural gas streams in late 2019, and feeds to the plant include natural gas from nearby fields in Utah.
- **Known resources of indium, aluminum, and fluorspar:** The West Desert zinc-copper-indium skarn deposit contains enough indium to supply current levels of U.S. consumption for 7 years, and the Blawn Mountain alunite deposit contains more than eight times the amount of alumina imported by the United States annually. The Lost Sheep fluorspar mine has produced enough fluorspar historically to account for more than 15% annual U.S. consumption.
- **Refinement of uranium and vanadium, potential mining restart:** Blanding, Utah, hosts the only operating conventional uranium and vanadium mill in the United States, and multiple uranium-vanadium mines on stand-by in southeastern Utah are prepared to re-establish mining under favorable economic conditions.
- **Prolific historical production:** Utah has historically been a major domestic producer of bismuth and has produced notable arsenic, antimony, barite, germanium, gallium, manganese, tellurium, and tungsten.
- **Rare earth element byproduct potential:** Limited geochemical sampling of the beryllium mine tailings at the Spor Mountain mine indicate potential enrichment in heavy rare earth elements, one of the most import-reliant commodities in the United States.

INTRODUCTION

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; in fact, the Strategic and Critical Materials Stock Piling Act was established in 1939. 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 also 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, which require a wider variety of materials than technology in previous decades. Changes in the production of minerals results 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 (e.g., most of a commodity comes from only one or two countries), governance risk, and potential impact of supply disruption. The increasing trend towards globalization of supply chains has added dimensions of complexity to evaluating these factors, since countries dominating a commodity market may not necessarily be the country with the largest geologic reserves. Raw ore or concentrates may be transported from the country where it is mined to other countries, often over substantial distances, for refinement into final products. China, for example, is the dominant global producer of refined cobalt, even though nearly 70% of mined cobalt comes from the Democratic Republic of the Congo.

The most recent focus on critical minerals began in 2017 when a presidential executive order (Executive Order 13817, A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals) directed the U.S. government to develop a strategy to mitigate foreign dependence on critical minerals. As part of the strategy, the U.S. Geological Survey (USGS) developed a list of 35 mineral-derived commodities (including both pure elements such as antimony and minerals or compounds such as potash). The United States is more than 50% import reliant on 31 of these commodities and has total import reliance for 14 of them. These critical minerals are aluminum (bauxite), antimony, arsenic, barite, beryllium, bismuth, cesium, chromium, cobalt, fluorspar, gallium, germanium, graphite (natural), hafnium, helium, indium, lithium, magnesium, manganese, niobium, platinum group metals, potash, rare earth elements group, rhenium, rubidium, scandium, strontium, tantalum, tellurium, tin, titanium, tungsten, uranium, vanadium, and zirconium (figure 1 and table 1).

Utah is fortunate to have abundant and diverse mineral commodities, including many of those currently identified as critical. As one of the top ten states for mineral production value for the past decade and the second most favorable mining jurisdiction in the contiguous United States in 2019, Utah is prospective for the development of domestic critical mineral resources. Utah is also host to three distinct geologic domains: the Basin and Range, 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, with support from a USGS National Geological and Geophysical Data Preservation Program (NGGDPP) grant, offers an overview of Utah's current and potential critical mineral production and diverse minerals landscape.

This report is divided into sections based on the degree of resource development: current producers, established resources, potential resources (including past producers), mineral occur-

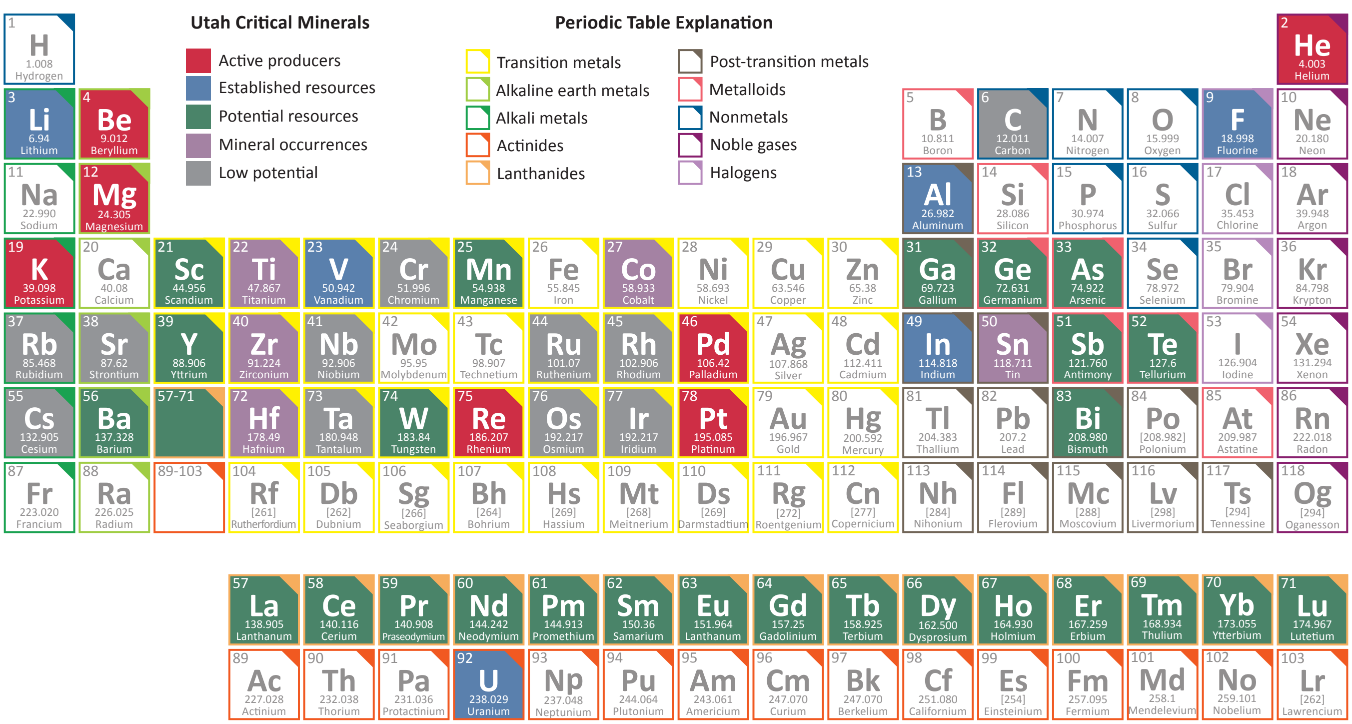

Figure 1. *Periodic table showing all 35 critical minerals identified by the U.S. Geological Survey, and those found in Utah highlighted according to their current resource status.*

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

Commodity	Element Symbol	Top Global Producer[1]	U.S. Import Reliance[1] (%)	Notable Utah Locations
Critical Minerals Currently Produced in Utah				
Beryllium	Be	United States (Utah)	3	Juab Co.
Helium	He	United States	0	Grand, Emery, San Juan Co.
Magnesium metal	Mg	China	<50	Great Salt Lake
Potash	K (KCl, K_2SO_4)	Canada	91	Great Salt Lake, Tooele Co. (Bonneville Salt Flats), Grand and San Juan Co. (Paradox Basin), Millard Co. (Sevier Lake)
Platinum and Palladium	Pt, Pd	South Africa, Russia	64, 32	Salt Lake Co. (Bingham mine)
Rhenium	Re	Chile	82	Salt Lake Co. (Bingham mine)
Established Critical Mineral Resources in Utah				
Aluminum	Al	Australia (bauxite)	>75 (bauxite)	Beaver Co.
Fluorspar	F (CaF_2)	China	100	Juab Co.
Indium	In	China	100	Juab Co.
Lithium	Li	Australia	>25	Great Salt Lake, Grand and San Juan Co. (Paradox Basin)
Uranium	U	Kazakhstan	90[2]	San Juan, Grand, and Emery Co.
Vanadium	V	China	94	San Juan, Grand, and Emery Co.
Potential Critical Mineral Resources in Utah				
Antimony	Sb	China	84	Garfield, Salt Lake, and Box Elder Co.
Arsenic	As	China	100	Tooele Co.
Barite	Ba ($BaSO_4$)	China	87	Juab and Tooele Co.
Bismuth	Bi	China	96	Salt Lake, Juab, and Tooele Co.
Germanium and Gallium	Ge, Ga	China	>50, 100	Washington Co.
Manganese	Mn	South Africa	100	Juab, Millard, Emery, Grand, San Juan, Tooele, Beaver, Piute, Utah, and Salt Lake Co.
Rare Earth Elements and Scandium	La, Ce, Pr, Nd, Pm, Sm, Eu, Gs, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y, Sc	China	100[3]	Juab and Tooele Co.
Tellurium	Te	China	>95	Salt Lake Co. (Bingham mine)
Tungsten	W	China	>50	Tooele, Box Elder, Juab, Millard, Beaver, and Salt Lake Co.
Minor Critical Mineral Occurrences in Utah				
Cobalt	Co	Congo	78	Emery, Grand, San Juan, and Garfield Co.
Tin	Sn	China	77	Tooele, Juab, Millard, and Iron Co.
Titanium, Zirconium, and Hafnium	Ti, Zr, Hf	China (Ti), Australia (Zr, Hf)	93[4], 0, not available	Garfield and Kane Co.
Critical Minerals with No Known Potential in Utah				
Cesium, Rubidium	Ce, Rb	Canada	100	
Chromium	Cr	South Africa	100	
Graphite	C	China	100	
Niobium	Nb	Brazil	100	
Other Platinum Group Elements	Ir, Os, Rh, Ru	South Africa	not available	
Strontium	Sr	Spain	100	
Tantalum	Ta	Congo	100	

[1]Source: U.S. Geological Survey Mineral Commodity Summaries
[2]Source: U.S. Energy Information Administration
[3]The U.S. exports a minor amount of mineral concentrates for processing, but is 100% reliant on imports of REE compounds
[4]Titanium mineral concentrates

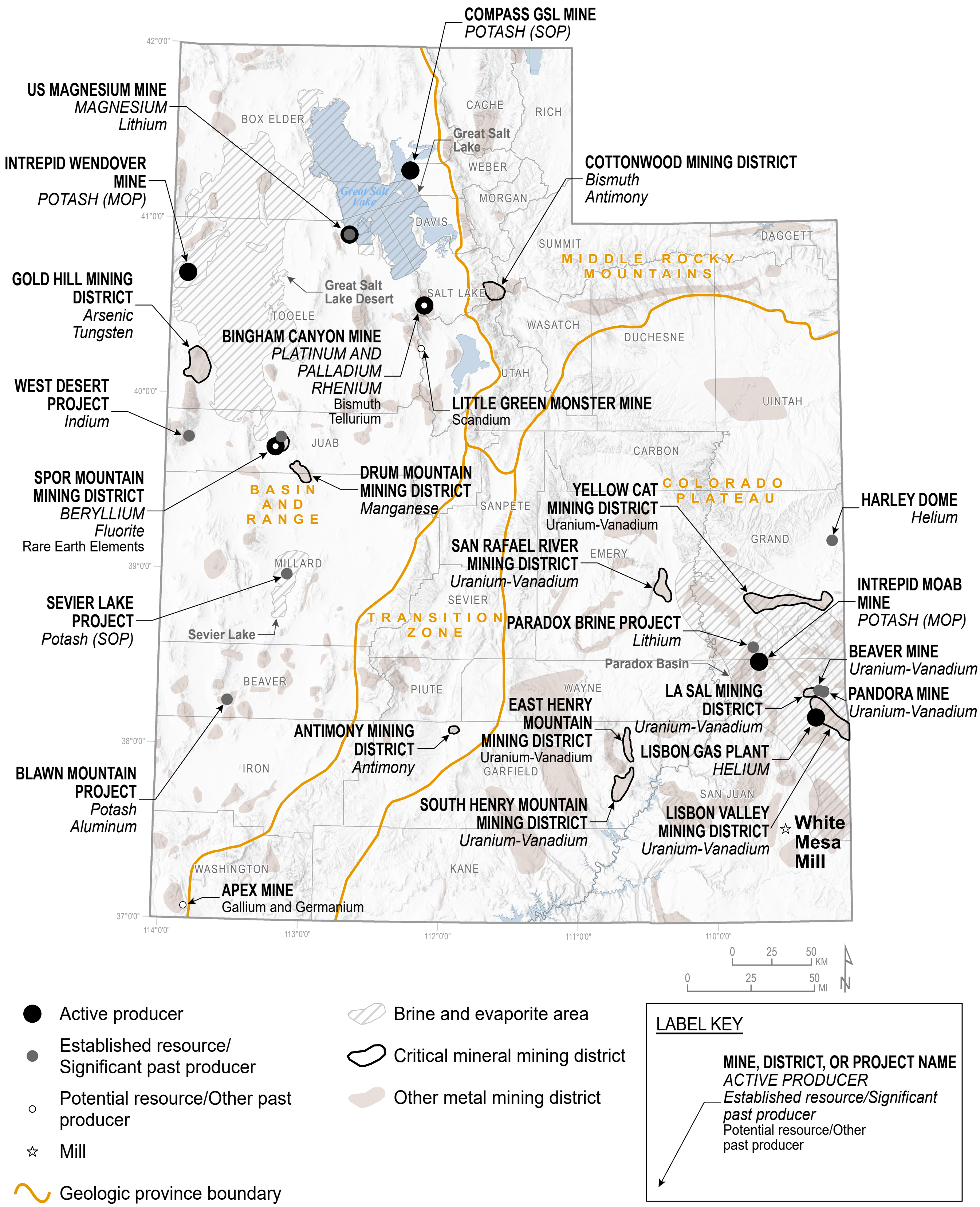

Figure 2. *Summary of the distribution of Utah's critical mineral resources. Active mines, established resources, and historically mined germanium, gallium, scandium, and tellurium are shown by points. Mining districts are highlighted for historically mined arsenic, bismuth, manganese, antimony, and tungsten, and for REE byproduct potential.*

rences, and minerals with no known potential for development in Utah. Current producers include 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 and palladium). Established resources are previous operations that have been recently idled or are on standby, or projects that have never been in production but have a published technical report detailing a resource estimate. Potential resources have been historically produced in Utah or are recognized as possible byproducts. Mineral occurrences represent areas of known 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 degree of resource development was based on the status of projects as of spring 2020, and projects may have progressed or been deprioritized since.

The information in this report is drawn from a variety of sources including USGS Mineral Commodity Summaries, Utah Geological Survey (UGS) annual mining surveys and historical documents, mining company websites, press releases, technical reports, the Utah Department of Oil, Gas and Mining website, and communication with industry geologists. References for each critical mineral are included at the end of the sections for additional commodity-specific sources.

CRITICAL MINERALS CURRENTLY 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, due to be launched in 2021, is composed of 18 gold-coated hexagonal beryllium mirror segments that will help it observe galaxies over 13 billion light-years away. 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 70% to 85% of beryllium is currently sourced from the Spor Mountain mine (figure 3), any compromise to the operation would have strong negative impacts on the entire beryllium supply chain.

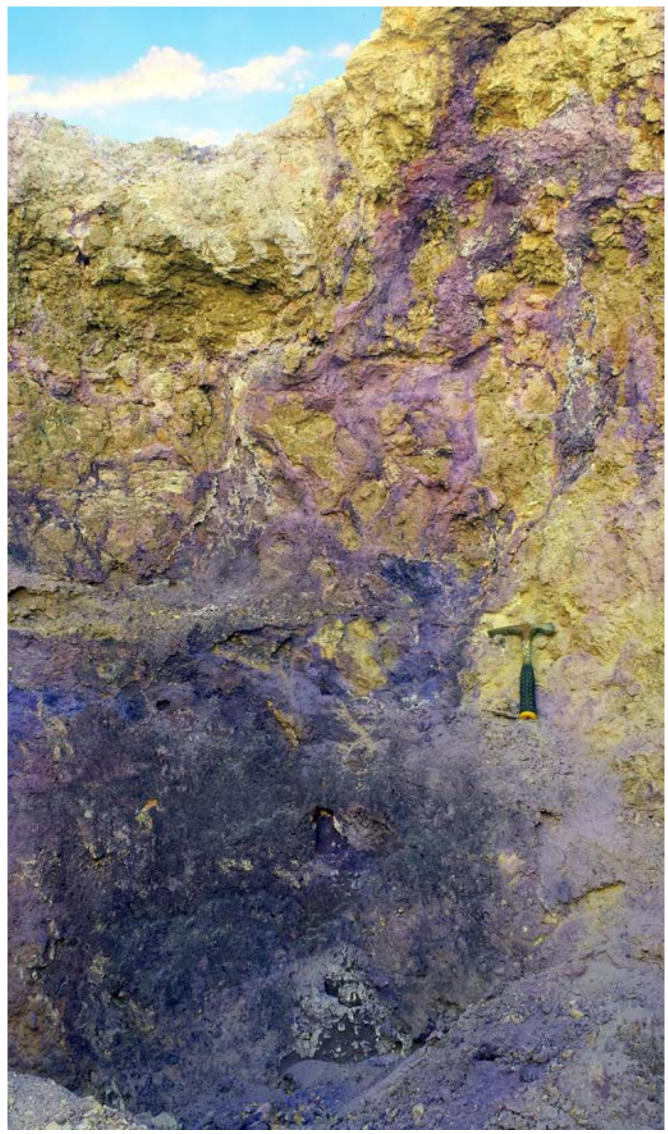

Figure 3. *Open-pit mining face in the Spor Mountain mine showing the distinct purple hue of bertrandite ore. The bertrandite itself is colorless but forms with purple fluorite, thus giving the ore the overall purple color.*

Sources and Geology

Beryl ($Be_3Al_2Si_6O_{18}$) and bertrandite ($Be_4Si_2O_7(OH)_2$, figure 4) 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 operations, 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).

Economic bertrandite deposits are volcanogenic in nature, though bertrandite can occur in vein-hosted carbonate replacement deposits or with beryl in skarn deposits. Spor Mountain 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 anomalous beryllium enrichment (figure 5), but the Spor Mountain mine 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 another company's 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 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 indefatigable lawyer who was hit with a shovel and had two ribs broken over the course of the dispute.

Figure 4. Replacement-style beryllium mineralization in a calcareous Paleozoic nodule from the Spor Mountain Formation. Bertrandite mineralization occurs with fluorite (the purple mineral), and additional replacement minerals include quartz, calcite, and chalcedony. Sample courtesy of Mark Milligan.

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 (figure 6), and mining has expanded from the initial Roadside pit to include ten pits. Materion reports indicate over 9.9 million tons proven and probable reserves, which is estimated to last a minimum of 75 years at the current rate of mining.

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

Utah Spotlight: Beryllium Belt

The so-called Beryllium Belt of western Utah (figure 7) was first defined by Cohenour (1963) and has remained a generalized term for a series of beryllium occurrences stretching east-west from the Tintic Mountains in central Utah to the southern Deep Creek Range near the border with Nevada. The 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

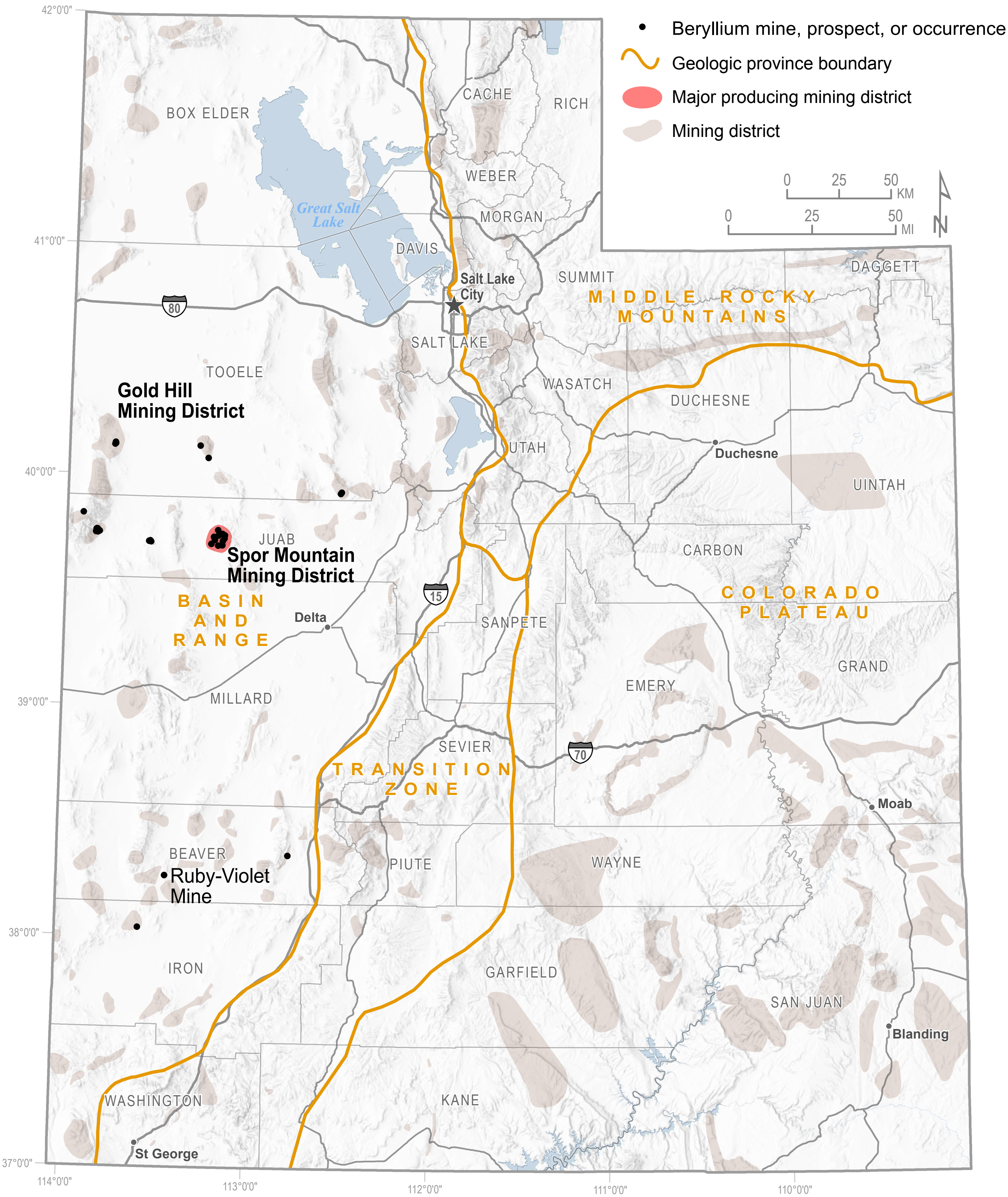

Figure 5. *Distribution of beryllium resources in Utah.*

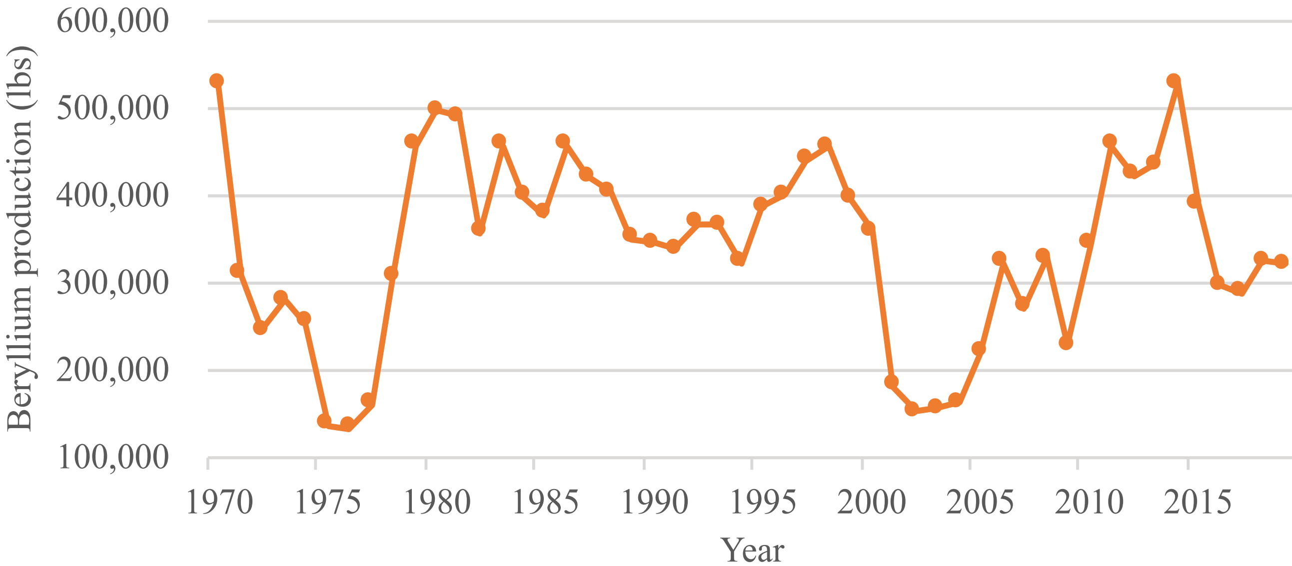

Figure 6. *The annual production of beryllium from the Spor Mountain mining and Delta milling operations. Bertrandite ore is mined from the Spor Mountain open pits and trucked to the mill in Delta, where it is converted to beryllium hydroxide. The beryllium hydroxide is shipped to plants out of state for further refinement into final products.*

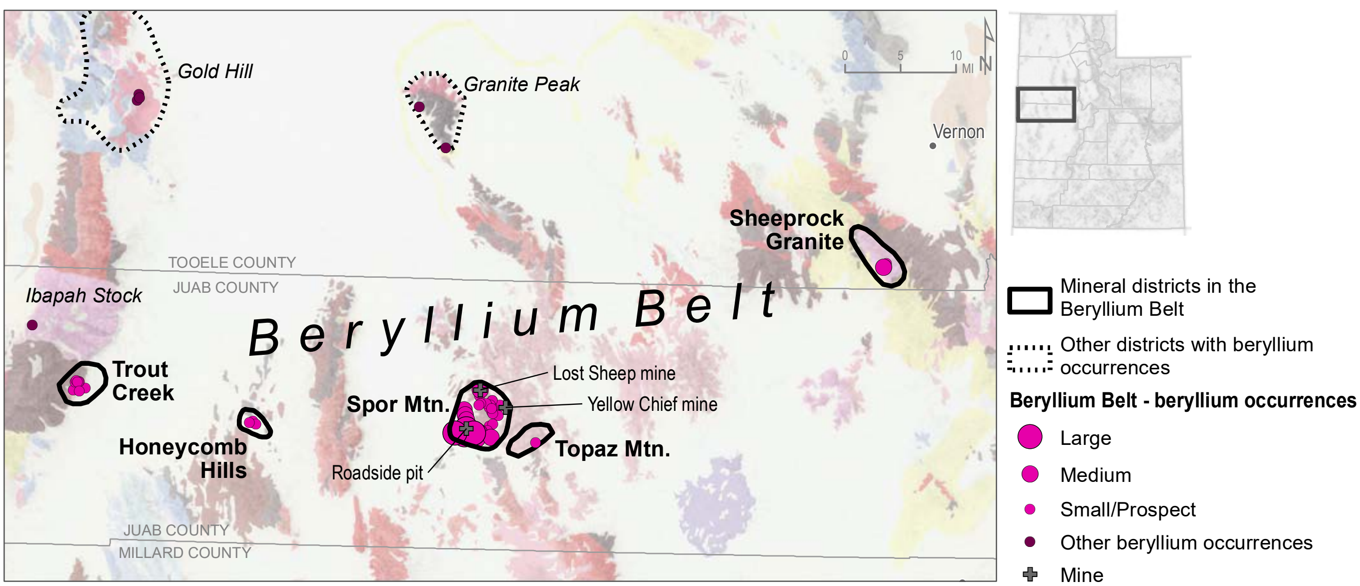

Figure 7. *Regional extent of the Beryllium Belt, a region in Utah known for highly evolved silicic and peraluminous intrusive and volcanic rocks with anomalous enrichment in beryllium. Geology base map from Hintze and others (2000).*

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. 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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Helium

Overview and Criticality

Helium is the second lightest element on the periodic table; it occurs as a gas and is colorless, tasteless, odorless, and inert. Helium's properties allow it to be used in a variety of ways, the most common being in MRIs (magnetic resonance imaging), analytical applications, welding, leak detection, semiconductor manufacture, and defense applications. Helium is also commonly used as a lifting gas for lighter-than-air aircraft.

Sources and Geology

Helium forms through radioactive decay of uranium and thorium in mineral grains commonly found in Precambrian basement rock, Paleozoic shales, and basement-derived sandstone. It accumulates similarly to oil and gas. Therefore, helium is most often produced as a byproduct or co-product of natural gas fields. A concentration of about 0.3% helium by volume in a natural gas stream is the lower threshold for considering helium as a potential resource. Due to the millions of years that it takes to form economically significant helium reservoirs and because helium can escape the atmosphere, helium is considered a non-renewable resource. Unique to other commodities, the U.S. federal government has been managing the production, refining, and storage of helium in the United States since 1925, but this situation is set to end by 2021. This change, along with recent global shortages of helium, is likely to spur interest in exploration for additional helium sources and contributes to helium's criticality. Most U.S. production comes from the mid-continent and Rocky Mountain regions and currently the United States is the largest producer of helium followed by Qatar and Algeria. The United States also has the largest known reserves followed by Algeria and Russia.

Helium in Utah

Utah's helium resource potential lies within the Colorado Plateau in the eastern part of the state, and available data suggest that most of that potential is found in Carbon, Emery, Grand, and San Juan Counties (figure 8). Analyses of gas stream data from oil and gas wells document potentially economic helium in Devonian- through Jurassic-age reservoirs. Currently, a gas plant in Lisbon Valley in San Juan County is purifying helium separated from natural gas streams. The plant began processing helium in 2019, some of which comes from the Lisbon oil and gas field and other nearby fields. A processing plant in Colorado is also producing some helium from the San Arroyo field in Utah's Grand County. However, the highest known concentrations of helium in Utah are in the Harley Dome field in Grand County, showing helium up to 7.3% in the gas stream from Jurassic reservoirs. In fact, from 2013 to 2018, 42 billion cubic feet of pure helium gas was produced from the field. Harley Dome was designated as a federal helium reserve in 1933 but was later made available for leasing in 1964. The extent of the resource at Harley Dome remains undefined.

Outside of Harley Dome, the majority of known helium concentrations in Utah are below 2%. However, several fields show concentrations well above the lower economic threshold of 0.3% helium. Some of the potentially important oil and gas fields are Big Flat and associated fields (Grand County; up to 1.7% helium), Boundary Butte and associated fields (San Juan County; up to 1.6%), Greater Cisco and associated fields (Grand County; up to 1.5%), the aforementioned Lisbon and associated fields (San Juan County; up to 1.3%), Salt Wash (Grand County, up to 1.8%), and Woodside (Emery County; up to 1.5%). Wildcat oil and gas wells in Emery County have also had helium shows of 2.8% and 1.5%. Although the helium resource related to these and other shows are not quantified, the data suggest that Utah could be an important supplier of helium in the future and further exploration would be warranted.

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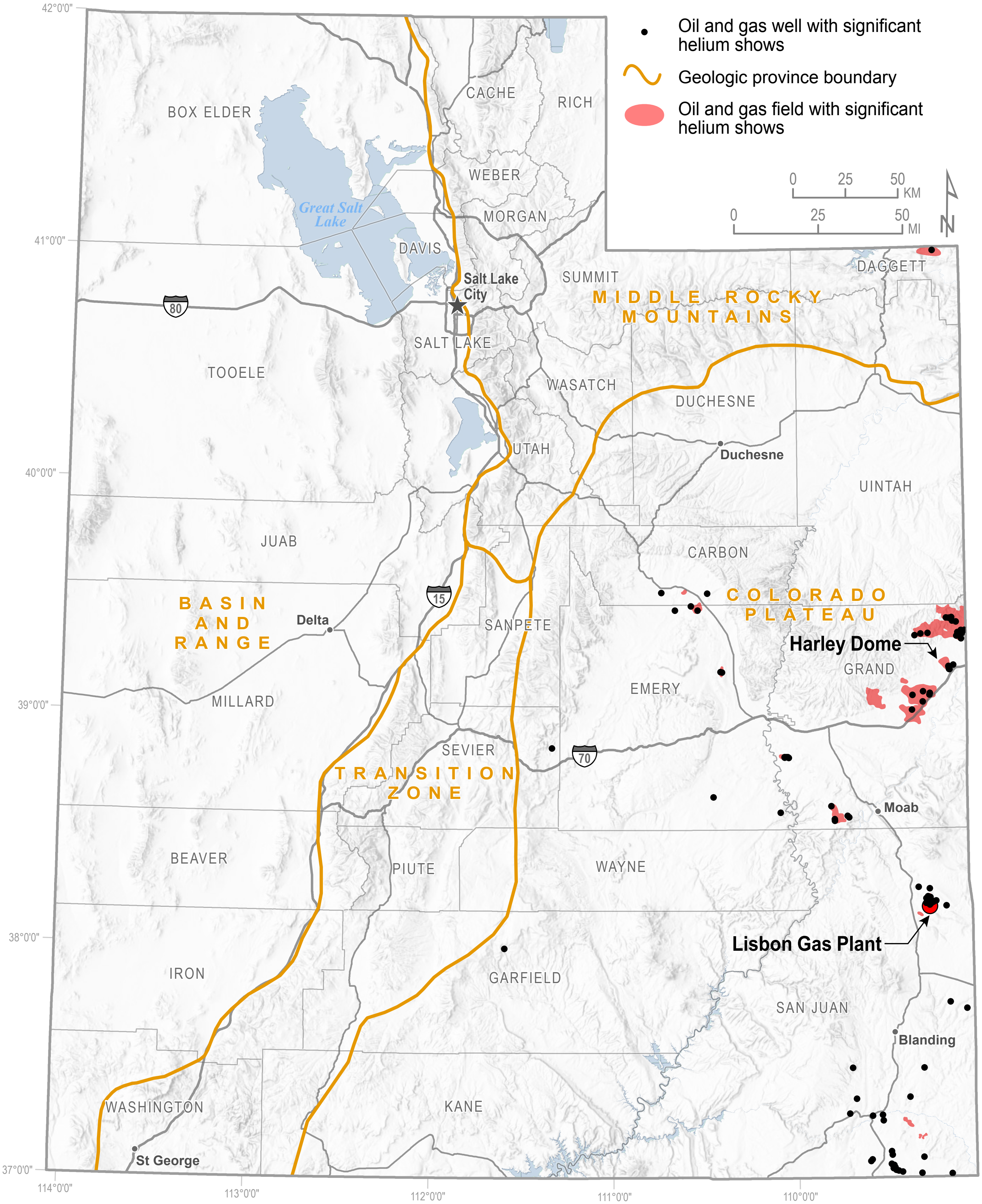

Figure 8. *Helium resources in Utah. Database of wells with significant shows provided by Tyler Wiseman.*

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, for example magnesium metal, magnesium chloride, magnesium hydroxide, caustic-calcined magnesia, and others. Magnesium metal is the form considered as a critical mineral. A significant use of magnesium metal is in alloys; magnesium can add strength, decrease weight, and increase corrosion resistance of alloys. Magnesium metal is commonly alloyed with aluminum for aerospace and defense applications. Additionally, magnesium metal 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 as a critical mineral 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 and the Dead Sea. 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. However, companies are actively pursuing domestic production of magnesium metal from dolomite. 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 $(Mg, Fe)SiO_4$. Olivine commonly occurs in mafic igneous rocks such as basalt, gabbro, or peridotite.

Globally, resources of magnesium are plentiful and sufficient to meet required demand, and China is the leading producer. The United States imports about half of its domestic requirement for magnesium metal, primarily 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 9 and 10). 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 or longer. The current trend of receding lake level may be a greater limiting factor to continued production than reduced magnesium levels in the brine. 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 ever 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 9). Brines in the Great Salt Lake Desert and Sevier Lake are genetically related to the relatively recent desiccation of the latest 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). 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. 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 County. Dolomitic

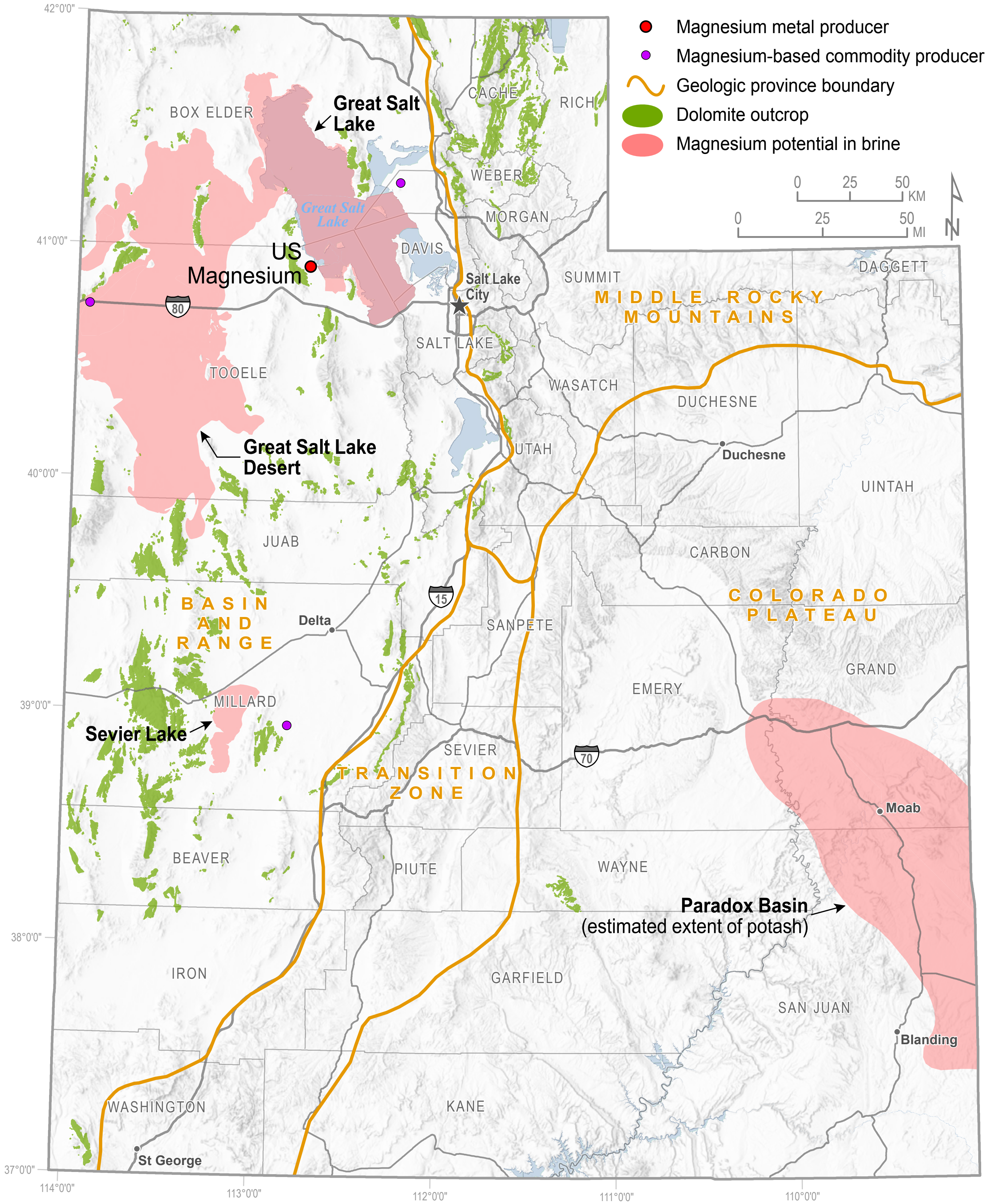

Figure 9. Magnesium resources in Utah. In the Paradox Basin, magnesium enrichment in brines is likely to be roughly coincident with the extent of potash mineralization.

Figure 10. *US Magnesium's operation on the west side of Great Salt Lake.*

Figure 11. *Great Salt Lake's north arm, Utah. Photograph was taken near the Spiral Jetty.*

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.

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. Great Salt Lake is a significant feature of Utah's physiographic, geological, and mineralogical landscape (figure 11). The terminal or closed basin nature of the lake has caused accumulation and concentration of dissolved solids and the resulting concentrated brine allows for economic extraction of multiple mineral commodities. 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. Anomalous levels of lithium in the lake could also lead to future production of lithium as a byproduct; US Magnesium is close to starting lithium production. Magnesium production 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. The titanium plant has been idle for the past few years but could be recommissioned if titanium sponge prices rise.

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Potash

Overview and Criticality

Potash refers to a variety of potassium compounds including potassium chloride (KCl, also known as MOP or muriate of potash), potassium sulfate (K_2SO_4, also known as SOP or sulfate of potash), potassium nitrate (KNO_3), and others. Most potash is used as fertilizer and is important to the food security of the United States because potassium is one of the three essential plant nutrients along with nitrogen and phosphorus. Potash also has a variety of chemical and industrial applications, such as production of soap, glass, ceramics, and batteries. In addition, it is used as an additive in drilling mud for oil and gas wells. Globally, the most common type of potash produced is MOP. Part of potash's critical status is the U.S.'s import reliance that currently stands at about 90%, 84% of which comes from Canada.

Sources and Geology

Most potash is sourced from deposits of bedded evaporites (or salts) that are often deep in the subsurface. These bedded salts are composed of minerals that have precipitated in the past in restricted marine basins (basins where seawater inflow and outflow are restricted). Because the basins are restricted, the seawater in the basins evaporates and salts become more concentrated. The ions in the concentrated seawater begin to precipitate as different salts based on the composition of the seawater, and in the late stages of precipitation, a variety of potassium-bearing compounds or salts can form such as sylvite (KCl), carnallite ($KMgCl_3{\cdot}6H_2O$), kainite ($KMg(SO_4)Cl{\cdot}3H_2O$), and langbeinite ($K_2Mg_2(SO_4)_3$). These and other potassium-bearing salts are the ore minerals from which potash is produced. Potash from evaporite deposits is either conventionally or solution mined. Solution mining involves pumping fluid into wells to dissolve the desired horizons and pumping the enriched fluid back out in other wells.

Potash is also produced from potassium-bearing brines, often from terminal lakes or groundwater brines associated with evaporite deposits. Potassium is extracted from the brine via harvesting of precipitated minerals in constructed evaporation ponds. For all deposits, including evaporite deposits and brines, the potash minerals being harvested require some level of processing to remove contaminants and to be transformed into a final product.

Some of the world's largest known potash resources are in Canada, Russia, Belarus, and China, but several other countries also have significant resources. Canada, Russia, Belarus, and China are also the leading global producers of potash.

Potash in Utah

Utah is one of two potash-producing states in the United States along with New Mexico, and Utah potash is sourced from both evaporite and brine (surface and subsurface) deposits. Two companies are currently producing potash from three different locations (figure 12). Compass Minerals produces SOP from brine of the north arm of Great Salt Lake, which is more concentrated than the lake's south arm. Compass's facility has an annual capacity of about 320,000 tons per year of SOP from its evaporation ponds and they estimate the Great Salt Lake resource will exceed 100 years of production at current rates. Compass can also produce additional SOP at this facility by converting supplemental MOP for a total annual SOP capacity of 550,000 tons. Intrepid Potash produces MOP from subsurface brine near the Bonneville Salt Flats in the Great Salt Lake Desert and from sylvinite (sylvite ore) in the Paradox Basin (figures 13

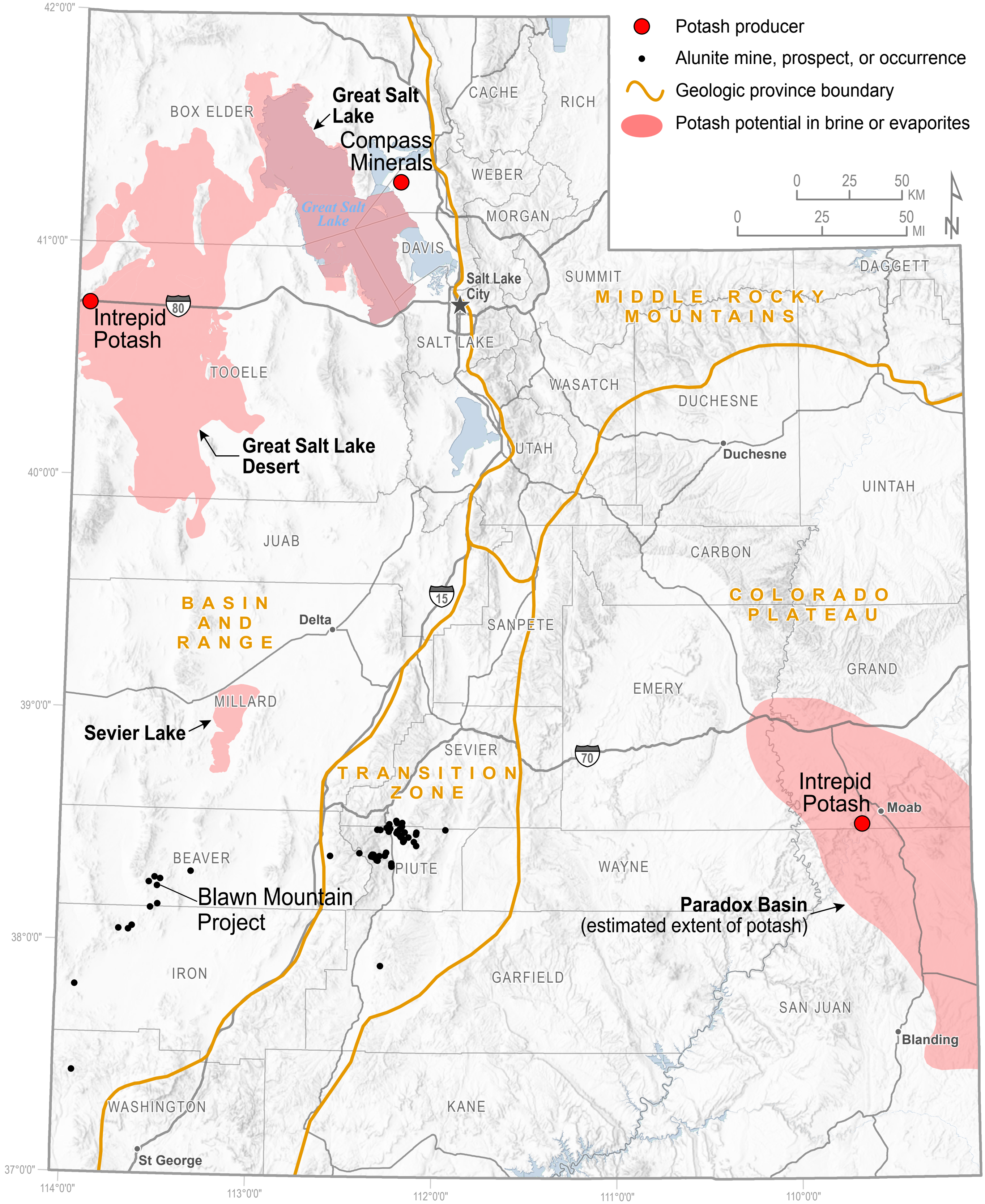

Figure 12. *Potash resources in Utah.*

Figure 13. *Intrepid Potash's evaporation ponds and processing facility near Wendover, Utah.*

Figure 14. *Intrepid Potash's evaporation ponds near Moab, Utah.*

and 14). At the Bonneville Salt Flats, near Wendover, Utah, potassium-rich brine from shallow and deep aquifers feeds Intrepid's evaporation ponds. This facility has a capacity of about 100,000 tons of MOP per year, and Intrepid estimates that the resource there will last a minimum of 30 more years. In the Paradox Basin near Moab, Utah, Intrepid Potash mines sylvinite via solution mining techniques from deep, subsurface evaporites formed during the Pennsylvanian (around 300 Ma). This operation has an annual capacity of about 110,000 tons per year of MOP and has proven and probable reserves of about 27 million tons of MOP, which is estimated to last 100 years or more. All of Utah's potash operations use evaporation ponds to precipitate potash minerals which are then processed to make the desired products. Utah is unique in that it produces two different types of potash. MOP is the most common type of potash produced globally, but SOP is a more valuable fertilizer that is currently priced at a few hundred dollars more per ton. Utah has produced about 350,000 to 500,000 tons of potash (combined MOP and SOP) per year over the past decade.

Beyond the resources that are currently being exploited, Utah has other known potash deposits that have been investigated, particularly in the past decade (figure 12). Crystal Peak Minerals has established a brine resource at Sevier Lake (or Sevier Playa) to produce SOP at a rate of about 370,000 tons per year for an estimated mine life of 30 years. The in-place measured and indicated resource of potassium sulfate at the project is 38 million tons, with a measured and indicated potentially extractable 10.5 million tons of potassium sulfate. The project is at an advanced stage and has received the necessary approvals from federal and state agencies to begin operation. Another company, SOPerior Fertilizer Corporation (formerly Potash Ridge) is developing a project in an alunite deposit at Blawn Mountain. Alunite is a hydroxylated aluminum potassium sulfate mineral ($KAl_3(SO_4)_2(OH)_6$) that is a less conventional, but proven source of potash and aluminum. The Blawn Mountain deposit is the largest known alunite deposit in the United States and SOPerior defined an in-place measured and indicated resource of about 32 million tons of potassium sulfate and a proven and probable reserve of about 10.6 million tons of potassium sulfate at their project. Utah also has other, smaller, scattered alunite deposits in the southwestern part of the state that are not as well defined.

Other companies have been evaluating the Paradox Basin evaporites in areas other than the one currently being mined. Potash resources of the Paradox Basin have been roughly estimated at around 2 billion tons, but that estimate is poorly constrained. Further exploration of the potash resource could make the basin an important potash producer in the future. In 2013, one company evaluated an area near Hatch Point and defined an in-place measured and indicated resource of 134 million tons of ore at a grade of nearly 19% potassium chloride along with a large inferred resource. A brine resource at Pilot Valley in the Great Salt Lake Desert has also been evaluated as a potential potash resource, but this deposit likely represents a smaller resource than the other deposits previously discussed.

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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, shares 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 Minnesota. However, these sources are not enough to cover domestic needs and about two-thirds of platinum and one-third of palladium are 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 found in only a few geologic locations globally. The main type of ore deposit hosting PGEs is magmatic sulfide deposits, 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, therefore the platinum and palladium produced in Utah are byproducts of other mining operations, namely porphyry copper mining at Bingham Canyon (figures 15 and 16). In general, North American porphyry copper deposits have very low concentrations of the platinum group metals, in part because they formed in a continental rather than island arc setting (figure 17). Although enriched in gold, Bingham Canyon hosts very low levels of palladium and almost no enrichment in platinum by comparison. The difference in PGE enrichment in the different porphyry settings is likely related to the parental magma bodies that generate porphyry stocks. In island arc settings, the parental magmas have a higher degree of asthenospheric mantle input or partial melting of subducted oceanic crust, which means there is more potential for PGEs to be enriched in the system. In continental systems, the parental magmas often have higher degrees of crustal assimilation, which would dilute the concentration of PGEs.

Despite the low levels of platinum and palladium in Bingham Canyon ores, the copper refining process is sophisticated enough to isolate whatever concentrations of PGEs are available (figure 18). Impurities in copper ores such as gold, silver, bismuth, tellurium, selenium, platinum, and palladium are removed during the electrolytic process that creates high-purity copper cathodes, and these impurities are gathered at the bottom of the electrolytic cell. From these impurities gold, silver, lead carbonate, and crude selenium are recovered. Platinum and palladium are concentrated in the crude selenium and refinement to their native metal forms is completed by consumers.

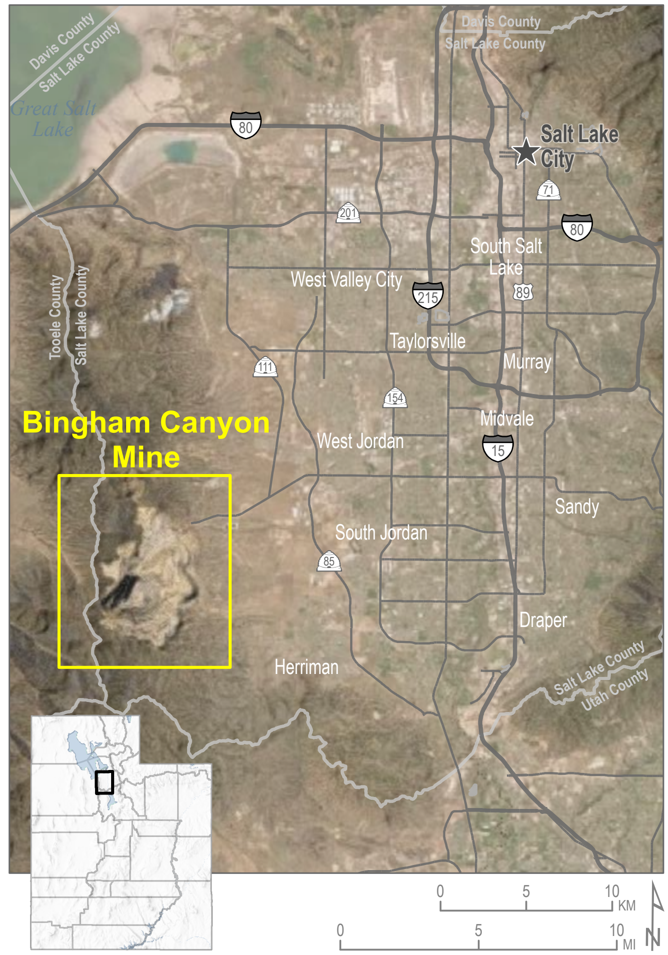

Figure 15. Location of the world-class Bingham Canyon mine west of Salt Lake City. Imagery from Esri, Digital Globe, GeoEye, Earthstar Geographics, cNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Figure 16. *The open pit at the Bingham Canyon mine.*

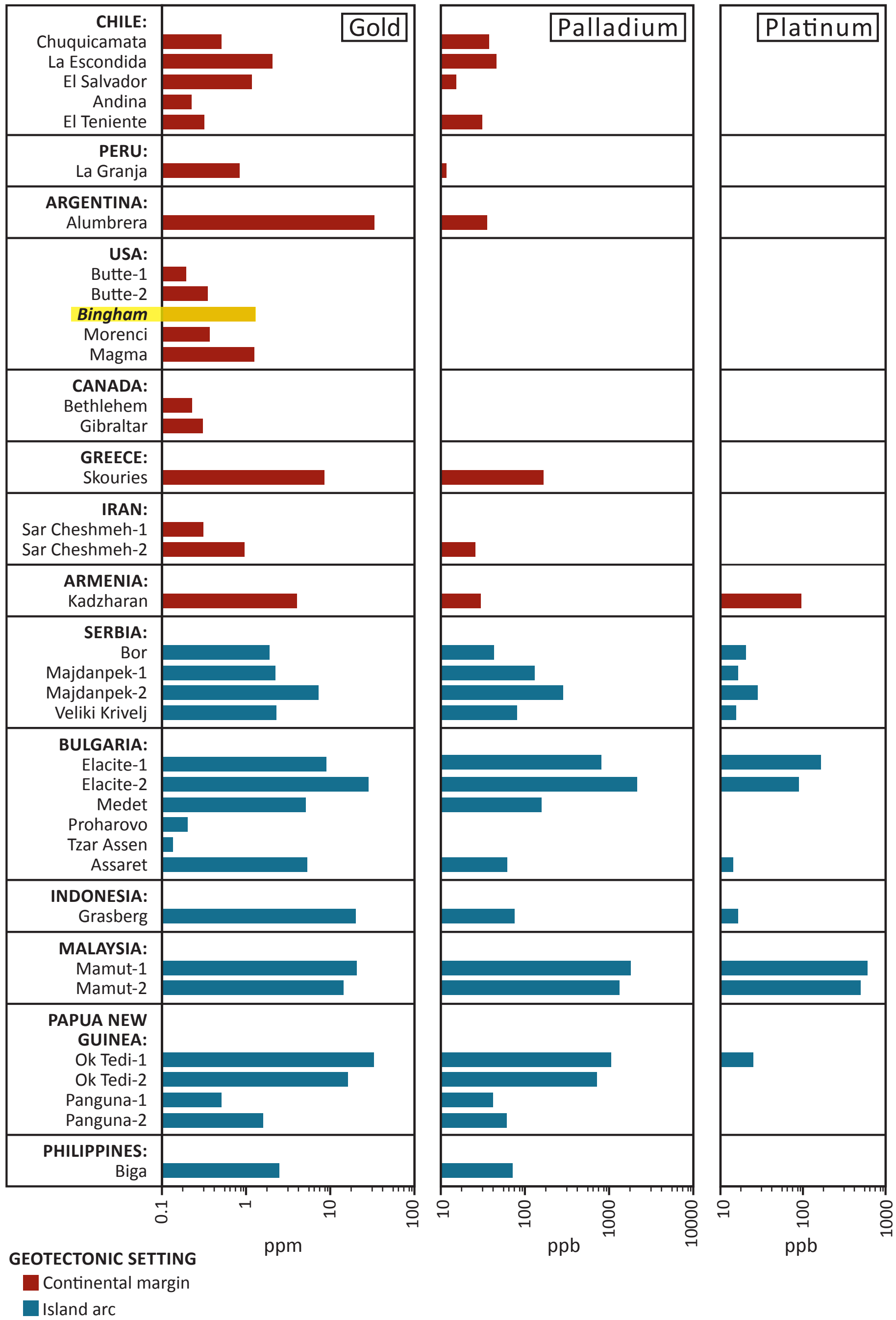

Figure 17. *Comparison of gold, palladium, and platinum content in concentrate samples from porphyry copper deposits in continental margin and island arc settings showing the low (below detection limit) platinum and palladium contents at Bingham Canyon. Adapted from Tarkian and Stribny (1999).*

Utah Spotlight: Bingham Canyon

The Bingham Canyon 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. Today Bingham Canyon is the second largest copper producer in the United States and has been in operation for over 100 years. Not only is ore mined from Bingham Canyon, it is also refined in Salt Lake County (figure 19). 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. 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 silica waste material. The copper concentrate is sent by pipeline to the smelter, the molybdenum concentrate is dried, bagged, and sent to domestic and international molybdenum refineries, and the tailings are sent by pipeline to a tailings

Figure 18. *Sulfide (pyrite, chalcopyrite) ore from the Bingham Canyon open pit mine.*

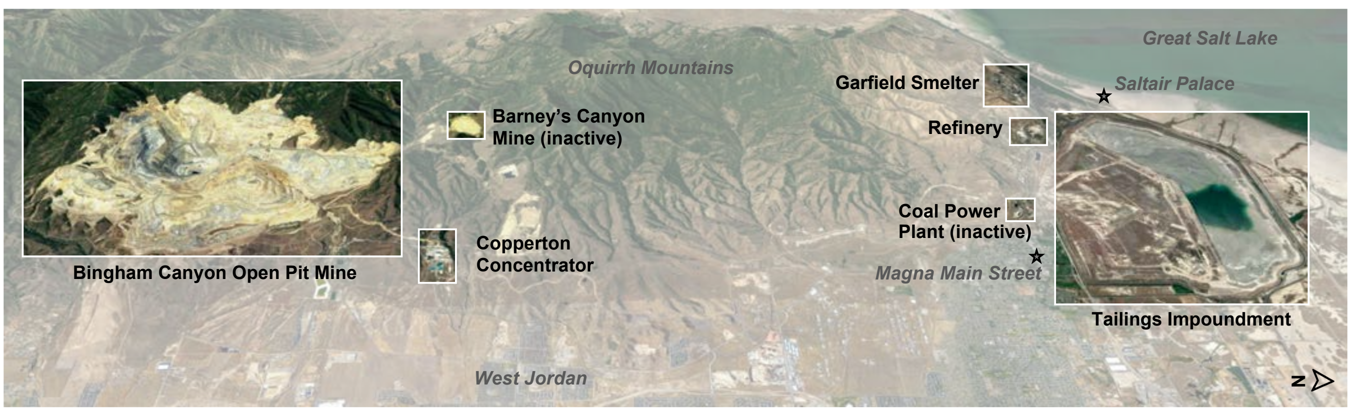

Figure 19. *The Kennecott Utah Copper Company operation west of Salt Lake City. Operations include the open-pit mine, concentrator, smelter, refinery, and power plant. Imagery from GoogleEarth, taken July 2019.*

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 report to the selenium "cake," which is sold for further processing by others.

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Rhenium

Overview and Criticality

Rhenium is a heavy transition metal and is chemically similar to manganese, both being in the same group on the periodic table. Like manganese, rhenium can exist in many oxidation states and has the widest range of valences of any element, ranging from -1 to +7. As one of the rarest elements in the earth's crust, rhenium is not mined as a principal commodity, rather it is recovered almost exclusively as a byproduct of molybdenum processing. Due to its uniquely high melting point (5767°F, third highest of all the elements) and stable crystalline structure under high temperatures, rhenium is primarily used in high-temperature alloys, such as for turbine blades in jet engines.

In the United States, high-temperature alloys represented 80% of rhenium use in 2019. Other applications include catalysts in the production of high-octane lead-free gasoline, high-temperature metallurgical uses, and a variety of electronic applications. The United States produces rhenium from domestic copper mining operations, but is still highly reliant on rhenium imports to meet demand. Due to the association of rhenium in copper porphyry deposits, most fully refined rhenium metal is imported from Chile, the world's leading copper-producing country. However, ammonium perrhenate (NH_4ReO_4), the most commonly traded form of rhenium, is sourced mainly from Kazakhstan, Canada, and Germany.

Sources and Geology

Rhenium is a chalcophile element, meaning it has a strong affinity for bonding with sulfur. It most commonly occurs in the mineral molybdenite (MoS_2) as a substitute for the molybdenum atom and can exist in concentrations up to several weight percent. Some of the rhenium that substitutes for molybdenum is radiogenic, meaning it decays into another element, in this case osmium. The amount of rhenium that has decayed to osmium can be used to date a molybdenite crystal, in the same way uranium and lead can be used to date a zircon crystal. The rhenium-osmium geochronologic system is the most reliable way to obtain the age of mineralization in an ore deposit, which may be substantially younger than the host rock.

Most rhenium is found in porphyry copper deposits, which are intrusions of granitic to dioritic magmas that release metal-rich hydrothermal fluids able to form fine-grained metallic minerals, such as chalcopyrite, throughout the host rock. Porphyry deposits are classified as low-grade, high-tonnage deposits, meaning they are mined on a large scale to recover enough metal to make the operation economic. Porphyry deposits are responsible for over half of global copper production, almost all molybdenum, and a significant amount of gold. Minor rhenium has also been recovered from sediment-hosted copper and uranium deposits, though these deposits contribute very minor amounts of rhenium to the global supply in comparison to porphyry deposits.

Rhenium in Utah

The Bingham Canyon porphyry copper deposit in Utah (figure 15) contains considerable amounts of byproduct molybdenum, and Bingham is often considered a porphyry copper-molybdenum-gold deposit. The molybdenite from Bingham ranges from 130 to 2000 ppm Re, averaging 250 ppm (figure 20). Globally, most rhenium (80%) is recov-

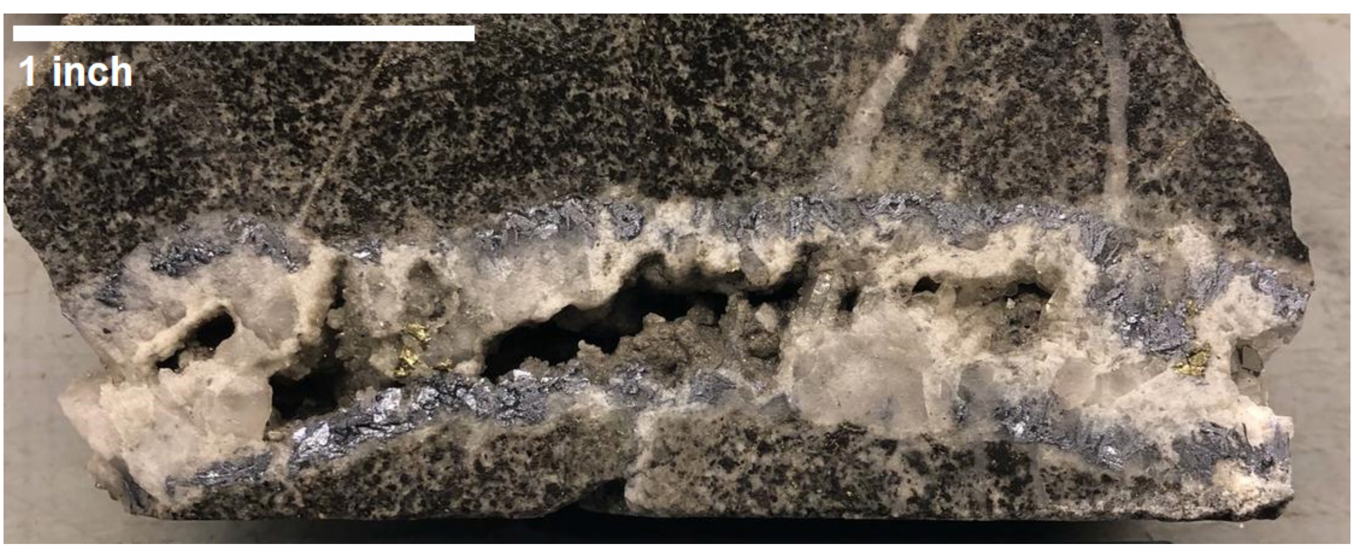

Figure 20. *Bingham Canyon molybdenum ore with a coarse molybdenite and quartz vein.*

Figure 21. *Kennecott Utah Copper Company's Garfield smelter located at the northern end of the Oquirrh Mountains.*

ered during the process of roasting molybdenite, the primary ore mineral of molybdenum. However, Bingham does not have a facility to process molybdenite ore and instead ships molybdenite concentrates to other facilities for processing. The Sierrita mine in Arizona is the only facility in the United States that processes molybdenite and recovers rhenium. So even though Bingham mines rhenium-bearing ore, they do not produce finished rhenium products from the molybdenite concentrate. However, in 2016 Bingham Canyon partnered with the U.S. Department of Energy's Critical Minerals Institute to investigate the possibility of recovering rhenium from the copper concentration process conducted at Bingham's facilities in Utah (figure 21) rather than from molybdenum. The method developed is designed to recover rhenium volatilized during the initial flash smelting step of the copper concentrate, which is captured in the off-gas scrubber solution. Rhenium is recovered as sodium perrhenate ($NaReO_4$) by processing the scrubber solution with an innovative continuous ion exchange process and could yield over 2000 lbs per year of rhenium, or roughly 2% of annual U.S. consumption. Development of the process continues, with a goal of producing a rhenium product for market in the near future.

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ESTABLISHED 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. Everyone benefits from aluminum on a daily basis from its presence in cars, boats, airplanes, power transmission lines, food packaging, and computers and other 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 U.S.'s 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, Australia, Vietnam, Brazil, and Jamaica. Currently, the largest bauxite producers are Australia, China, Guinea, Brazil, India, and Jamaica.

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 and alunite. Overall, global aluminum resources are plentiful and sufficient to meet current and future needs and production dynamics will generally be driven by economics.

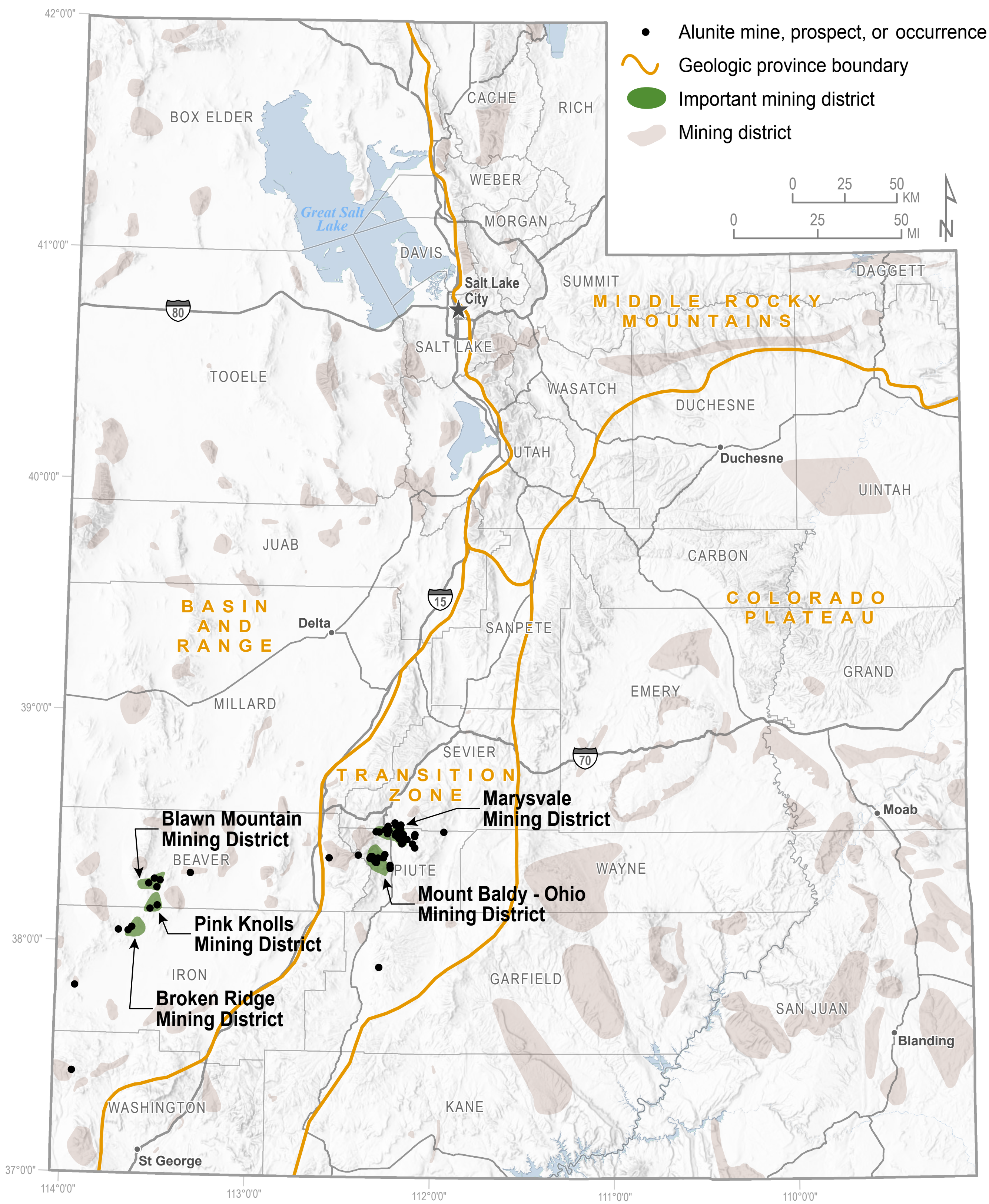

Figure 22. *Alunite resources in Utah.*

Aluminum in Utah

No substantial production of aluminum has occurred in Utah, but the state has significant alunite resources (figure 22). In fact, Utah boasts the largest alunite deposit in the country. Alunite is a hydroxylated potassium aluminum sulfate mineral ($KAl_3(SO_4)_2(OH)$, figure 23), and Utah has 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 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 last few years by SOPerior Fertilizer Corporation (formerly Potash Ridge) for production of potassium sulfate; alumina would be a byproduct or co-product. A 2017 technical report 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 better represents 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 clay deposits, but these deposits are unlikely to be economic and are currently poorly defined.

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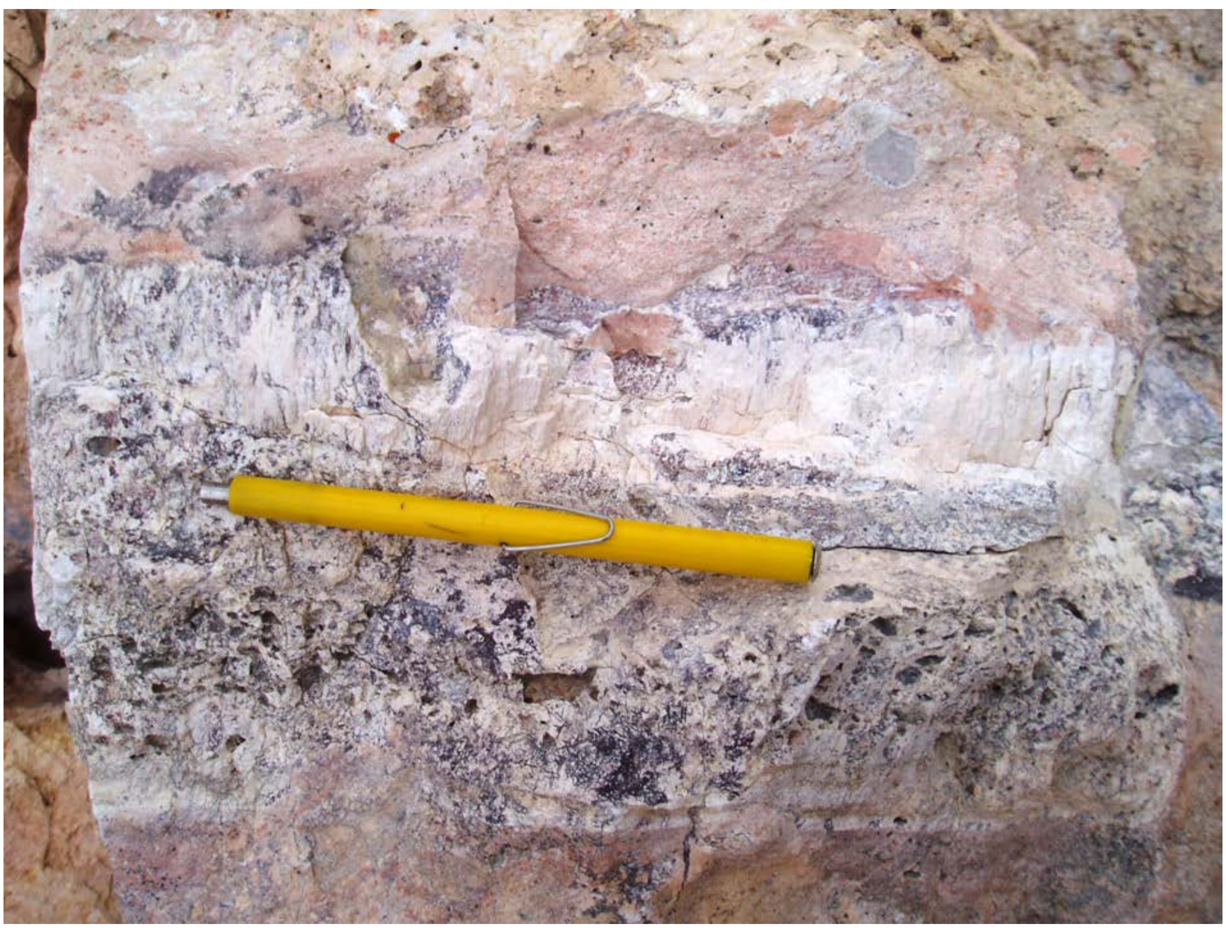

Figure 23. *Alunite vein in massive quartz-alunite sample from Blawn Mountain.*

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 produce 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 last 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 had a roughly estimated 50,000 tons of remaining known resources. Some fluorspar has been mined since 1975, 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 area (figure 24), and the predominant deposit type is breccia pipe fillings and replacements in dolomites adjacent to faults. The fluorspar at Spor Mountain occurs in a variety of ore textures: pulverulent, boxwork ore, aphanitic, sponge, and crystalline. Although substantially less than the Spor Mountain area, most of Utah's remaining production came from the Indian Peak Range, southern Wah Wah Mountains, and the Star Range in Beaver County (figure 24).

The largest producing fluorspar mine in Utah is the Lost Sheep mine in the Spor Mountain area. Prior to 1975, the mine produced about 90,000 tons of fluorspar, but an additional 8000+ tons was produced from 1993 to 2007. The mine is currently in the process of being reopened and produced a limited amount of fluorspar in 2018. The remaining, available resource at the mine is unknown. Overall, potential for discovery of additional fluorite resources in Utah is unknown, but the Spor Mountain area has the highest potential.

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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 transparent and colorless when applied as a thin coating to glass. It is also electrically conductive which, paired with its transparency, makes it an integral component to almost every flat panel display screen and touchscreen, such as for laptops and mobile phones. There are very few substitutes for indium and ITO. Given the total import reliance for the United States, the 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. As such, the leading sources of indium are deposits with significant zinc mineralization, such as volcanogenic massive sulfide (VMS), sediment-hosted exhalative (SEDEX), and Mississippi Valley-type (MVT) deposits. Globally, most zinc smelters are not equipped with refineries able 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, mainly from VMS and SEDEX deposits with lesser input from MVT deposits. In addition to VMS, SEDEX, and MVT deposits, indium also occurs in tin-rich polymetallic deposits in Bolivia and Canada. These deposits occur as veins and breccias in a variety of country rocks. The indium still occurs with zinc mineralization, because indium occurs in solid solution with sphalerite (ZnS). Indium, which has a 3+ charge, couples with Cu, which has a 1+ charge, to replace zinc and/or

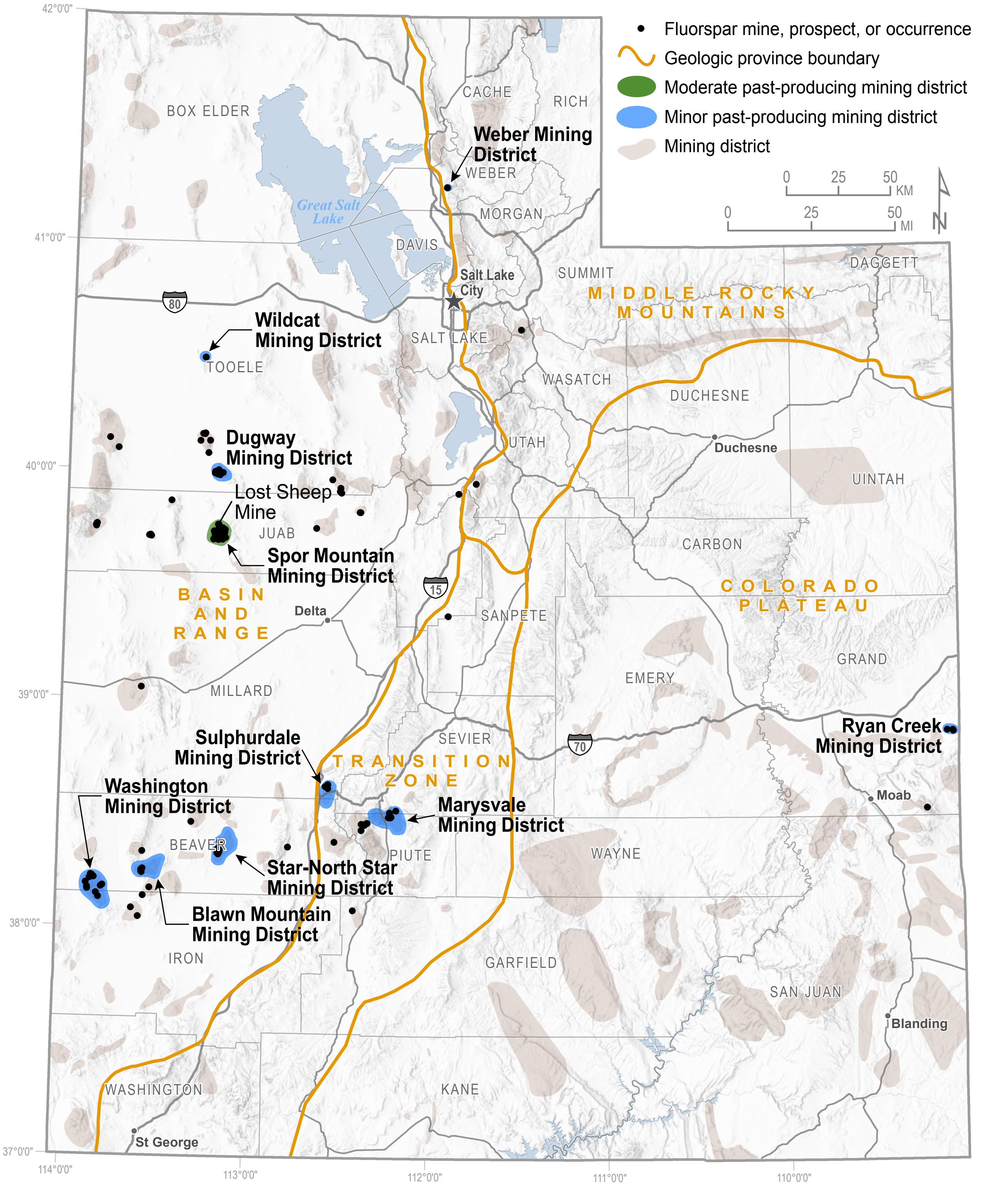

Figure 24. Fluorspar resources in Utah.

iron, both of which have a 2+ charge for a total coupled substitution of 4+ charge. Indium has been shown to account for nearly 7 wt. % of a sphalerite crystal in tin-rich polymetallic deposits, whereas the concentrations in VMS, SEDEX, and VMS deposits tend to be less than 1 wt. %.

Indium in Utah

Utah has only a few known indium occurrences (figure 25), the most significant of which is the West Desert deposit. The West Desert zinc-copper-indium-magnetite project (formerly known as the Crypto project) is located in the Trout Creek mining district in west central Juab County (figure 26). The deposit is located on the northwestern edge of the Fish Springs Range, which is a roughly north-south-trending range in the eastern Basin and Range composed of Paleozoic platform carbonates. The West Desert deposit occurs as skarn mineralization related to the intrusion of an Eocene quartz monzonite. Mineralization occurs in shales interbedded with massive carbonates and is separated into the Main and Deep zones by the extensional Juab fault. The hanging wall Main zone mineralization occurs in the Ordovician Wah Wah Limestone and

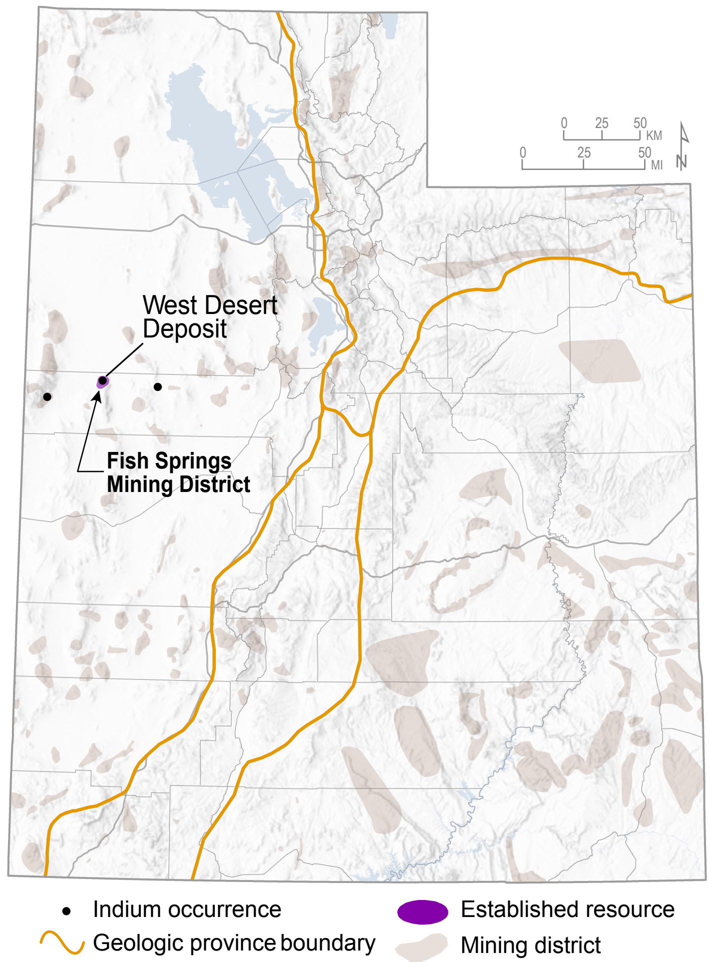

Figure 25. *Distribution of indium deposits and prospects in Utah.*

Figure 26. *The West Desert zinc-copper-indium-magnetite project is hosted in the Fish Springs Range, pictured here. Photo from Dyer and others (2014).*

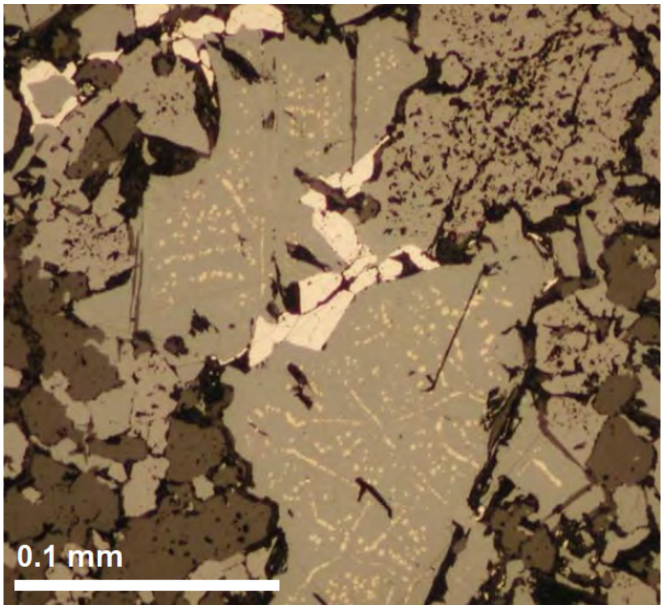

Figure 27. Reflected-light photomicrograph showing sphalerite (dark gray) with chalcopyrite inclusions from the West Desert project. The sphalerite was measured by energy dispersive X-ray (EDX) analysis as having indium concentrations over 9 wt. %. Photo from Dyer and others (2014).

the Kanosh Shale. The footwall Deep zone mineralization occurs in the Corset Spring and Candland Shale Members of the Cambrian Orr Formation. Skarn mineralization in both zones is characterized by magnetite with sphalerite and lesser chalcopyrite. Indium is hosted in sphalerite in concentrations up to 9 wt. %, far exceeding indium concentrations measured at other base metal deposits (figure 27). An estimated 3.5 million lbs (1770 tons) of indium is present in the deposit. The United States consumed 120 tons of indium in 2019, hence the West Desert project contains enough indium to supply the entire current U.S. consumption for over 14 years.

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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 devices and electric cars. Demand for lithium has risen sharply in the last 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 main 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 ($LiAl(SiO_3)_2$), but lepidolite ($K(Li,Al,Rb)_2(Al,Si)_4O_{10}(F,OH)_2$), petalite ($LiAlSi_4O_{10}$), and a few others have also been sources.

While 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 nature. Lithium-rich brines also require a source of lithium, often in the form of volcanic rocks, lithium-rich clay, or evaporite deposits that it can leach from. The only domestic lithium production comes from a brine deposit in Nevada, where average concentrations of lithium in the brine are around 160 ppm, which is on the low end of global lithium-from-brine producers.

Lithium in Utah

Due to recent rising demand for lithium, there has been a corresponding rise of interest in Utah's potential resources. Most of the attention has been focused on lithium potential in Utah's brine resources (figure 28); however, the brines have a high magnesium-to-lithium ratio and relatively low concentrations of lithium. Separating magnesium from lithium

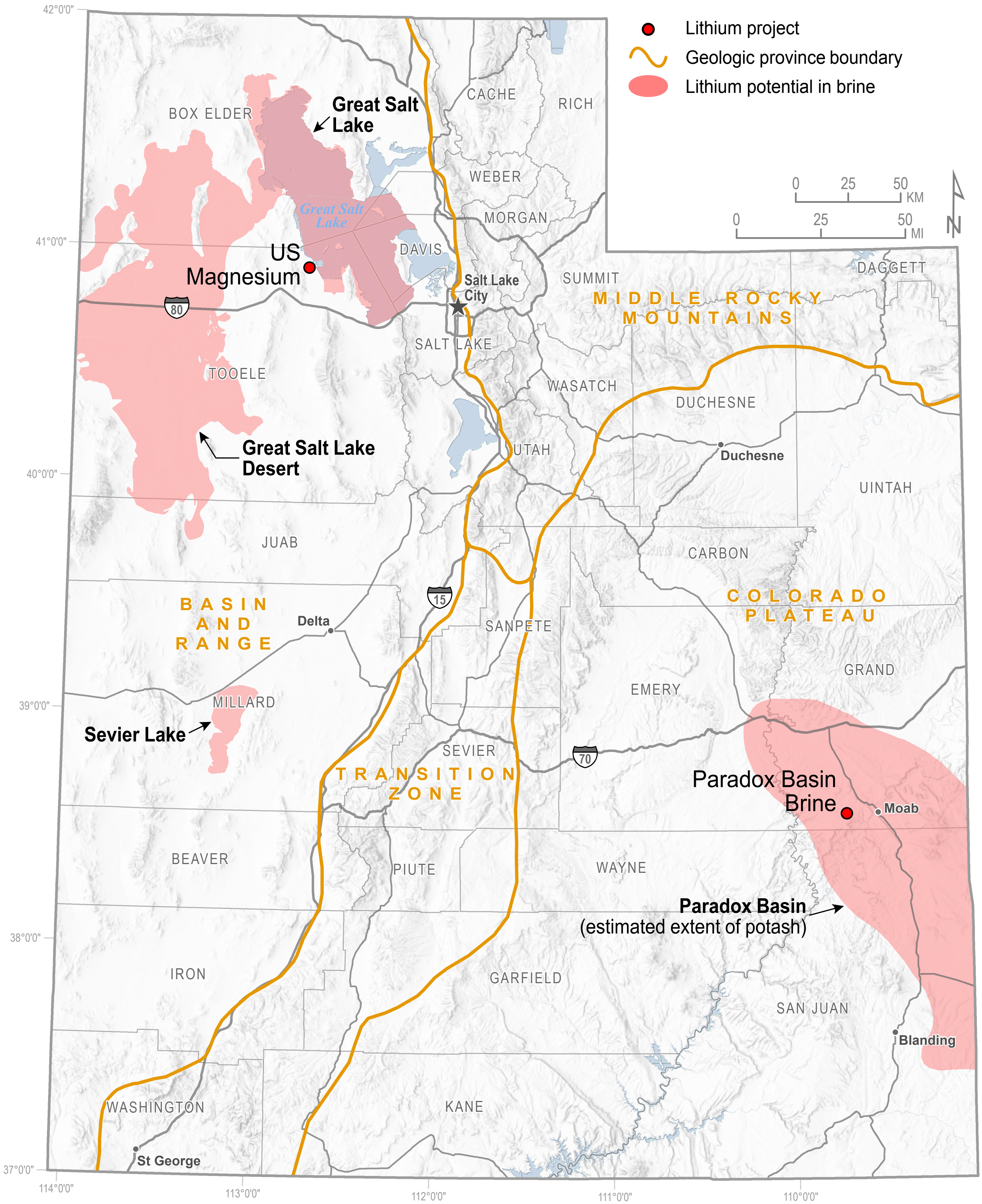

Figure 28. *Potential lithium resources in Utah. In the Paradox Basin, lithium enrichment in brines may be somewhat coincident with the extent of potash mineralization.*

is expensive and current technology and economics require a maximum ratio of magnesium-to-lithium of around 10 to 1. For most of the brines in Utah, the ratio is much higher, ranging from roughly 40 to 1 to 250 to 1. Maximum lithium concentrations in Great Salt Lake are around 80 ppm, which is below the average grade of current global lithium producers, though lithium concentration in the lake varies by location and lake level. New lithium extraction technology may change the ability to extract lithium economically from magnesium-rich brines in the future. Despite the magnesium-to-lithium ratio, part of US Magnesium's process to produce magnesium metal from Great Salt Lake requires separation of lithium from the magnesium-rich brine feedstock. This processing step may make lithium in Great Salt Lake an economically viable byproduct. Reportedly, US Magnesium is set to produce lithium in the near term.

Lithium exploration companies have also explored brines elsewhere in Utah, including the Paradox Basin. In the deep subsurface of the Paradox Basin, thick evaporite layers contain enriched groundwater brines. Old analyses from oil and gas wells show lithium concentrations in the low hundreds of parts per million. Recently one company, Anson Resources, has re-entered a few abandoned oil and gas wells and encountered lithium concentrations of up to 240 ppm. Anson is seeking to develop new lithium extraction technologies and has completed a resource assessment in an area west of Moab (the Paradox Basin Brine project), containing an in-place indicated and inferred 287,000 tons of lithium carbonate equivalent and a recoverable indicated and inferred 205,000 tons of lithium carbonate equivalent.

Brines of the Great Salt Lake Desert have also attracted some interest. Brines at the Bonneville Salt Flats and Pilot Valley show lithium concentrations of up to about 140 ppm and 100 ppm, respectively, but average concentrations are likely substantially lower. Overall, 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. However, magnesium contamination would still need to be addressed with expensive processing or new technologies.

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Uranium

Overview and Criticality

Uranium has been known since ancient Roman times when it was used to color glass for mosaics. Uranium was identified as an element in 1789, and its radioactive properties have been known since 1896. Early uranium mining in the late 19th century was focused on radium or vanadium, with the uranium recovered as a byproduct or discarded as waste. However, with the discovery of nuclear fission in 1938, uranium became a primary exploration target, both globally and in the United States.

Uranium has been classified as a fuel mineral since the 1970 Mining and Minerals Policy Act. The USGS identified nonfuel uses such as radiation shields, counterweights, armor piercing kinetic energy penetrators, and medical isotope production, which qualify uranium as a critical mineral (all other critical minerals are non-fuel minerals). The United States produces less than 10% of the uranium needed for domestic demand. Canada and Australia, which are the second and third leading producers of uranium in the world, respectively, supply nearly half of the uranium imported to the United States, with significant contributions also from Russia and Kazakhstan.

Sources and Geology

Uranium is a relatively common element and occurs in rocks all over the planet and even in seawater at low concentrations. Despite being a relatively common element, uranium forms concentrated economic deposits in only a few places globally. Uranium is a mobile element under oxidizing conditions and hence can be found in many types of deposits—in 2000 the International Atomic Energy Agency defined fifteen different types of uranium deposits, many of which have subtypes. The uranium deposits in Kazakhstan are mainly sediment hosted, whereas those in Canada are unconformity related. In Australia, which hosts 30% of known recoverable uranium resources, deposits are mostly unconformity related with the exception of the world-class Olympic Dam mine, which is a significant uranium resource hosted in an iron oxide breccia complex. As with the variety of uranium deposit styles, there are many different uranium ore minerals. Carnotite ($K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$) is one of the best known of these minerals, due to its bright yellow color, and is particularly common on the Colorado Plateau, where it was first discovered.

Uranium in Utah

Uranium in Utah is mainly found in sediment-hosted uranium deposits of the Colorado Plateau (figure 29). This geologic province has been the main source of uranium mining in the United States and includes areas of Utah, Colorado, New Mexico, and Arizona. Uranium mining from the Colorado

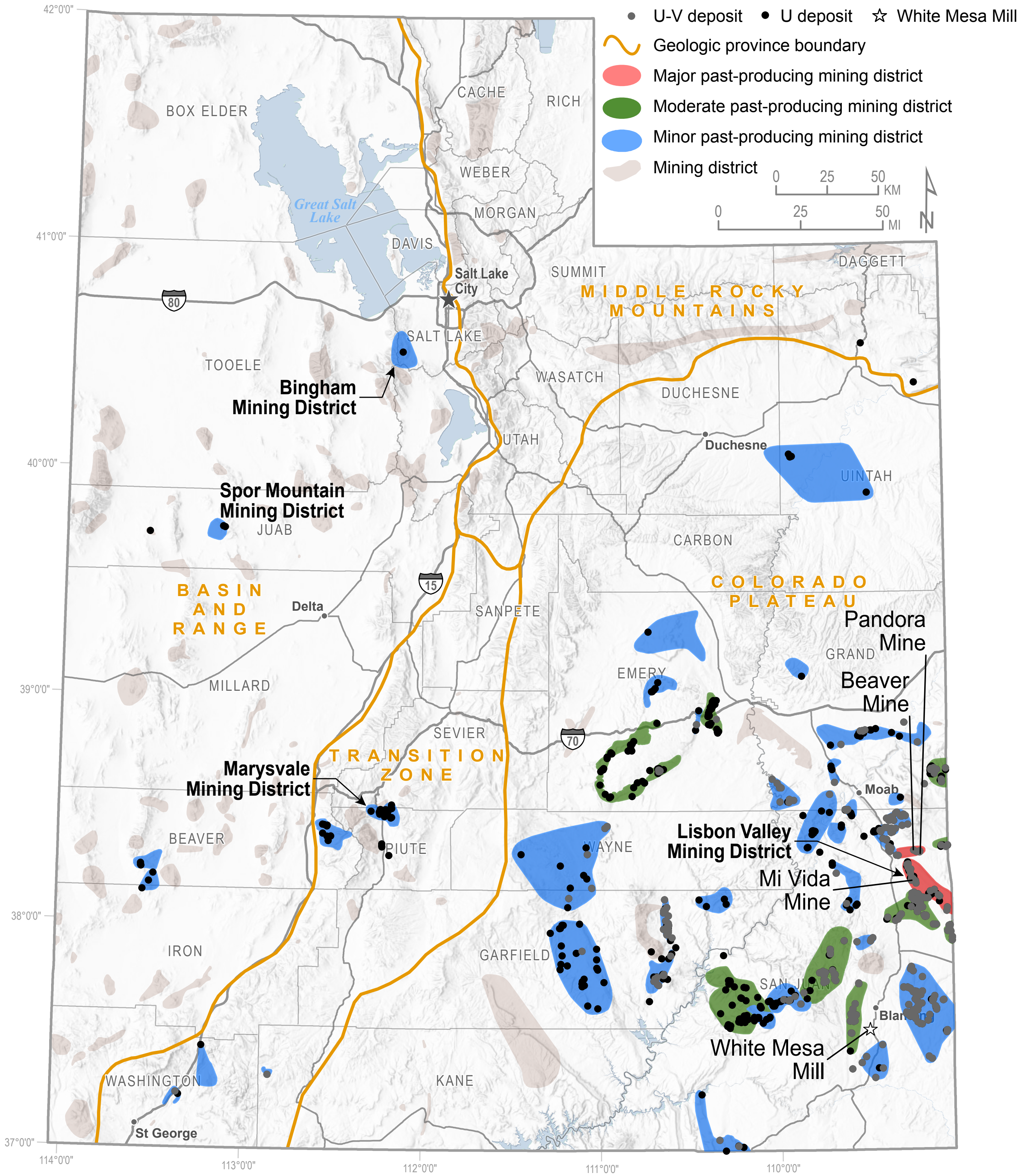

Figure 29. *Distribution of uranium-vanadium resources in Utah.*

Plateau led the United States to a position of dominance in the global uranium market from the early 1950s to late 1970s, starting with the discovery of the Mi Vida uranium mine in Utah's Lisbon Valley mining district in 1952 (figure 30). In Utah, uranium is hosted largely in the Jurassic Morrison Formation and the Triassic Chinle Formation. Uranium mineralization is hosted in sandstone lenses or beds with ore minerals filling pore space or replacing organic material and clays, often as the mineral uraninite (UO_2, figure 31). Although the Colorado Plateau accounts for more than 95% of uranium produced in Utah, other districts that produced notable uranium include the Marysvale, Bingham, and Spor Mountain districts. The Marysvale district, located in the transition zone between the Basin and Range to the west and the Colorado Plateau to the east, hosts uranium mineralization in veins and breccias in Miocene-age volcanics. The Spor Mountain district, known for beryllium production, hosts uranium in tuffaceous sandstones and conglomerates, in a similar sediment-hosted style to the Colorado Plateau deposits. The Bingham Canyon porphyry copper deposit does not contain significant uranium ore minerals, but uranium was recovered as a byproduct of copper processing during peak uranium prices in the late 1960s. In modern times, uranium mining is focused on the Colorado Plateau, but there has been no active mining since 2012. The only operating conventional uranium and vanadium mill in the United States (White Mesa Mill) is located in Blanding, Utah, and it processes uranium from other domestic mining and mine remediation operations. Multiple uranium mines throughout southeastern Utah such as the Beaver and Pandora mines remain on standby in anticipation of restarting under favorable economic conditions.

Figure 31. *Hand sample of high-grade uraninite mineralization replacing "plant trash" (carbonaceous detritus) in sandstone. Sample from the Snow mine in the San Rafael Swell mining district, Emery County.*

Utah Spotlight: Colorado Plateau

The Colorado Plateau is a physiographic and geologic region covering southeastern Utah, northeastern Arizona, northwestern New Mexico, and southwestern Colorado. The area is characterized by high-altitude, semi-arid environments with scattered forests. In Utah, the plateau is home to some of the most scenic state and national parks, such as Canyonlands and Arches. The 25-mile-thick crustal block comprising the plateau has experienced little deformation in the past 500 million years in contrast to the strongly folded and extended Basin and Range 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 Plateau experienced minor magmatism, as can be seen in the La Sal and Henry Mountains, though it is not the magmatic systems that contribute to the most significant mineralization on the plateau, as in other geologic terranes such as the Basin and Range. Rather, the Colorado Plateau's sediment-hosted uranium and vanadium deposits tend to form in sandstone or shale lenticular and tabular fluvial channels (figure 32). Mineralizing fluids are thought to be associated with low-temperature groundwater flow during the Mesozoic Era. The groundwater contained low concentrations

Figure 30. *The Mi Vida uranium mine, discovered by Charlie Steen in 1952. The discovery of the Mi Vida mine kicked off the uranium rush in the Colorado Plateau.*

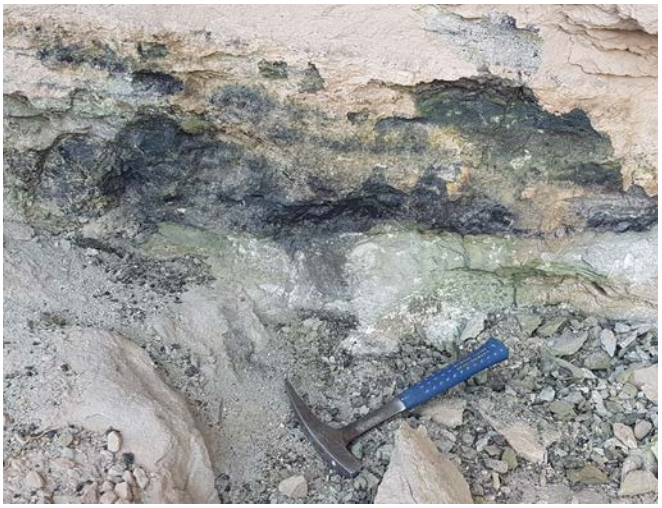

Figure 32. *Massive uranium mineralization, dominantly uraninite (black), hosted in sandstone in the Temple Mountain mining district, Emery County.*

of uranium that were progressively deposited in organic-rich sites (e.g., plant detritus) over long periods of time, eventually forming large deposits. The source of the uranium has been hypothesized as surface rock and soil, leaching of permeable strata in the region, or hydrothermal solution from the basement. Hydrothermal, saline basin brines sourced from Paradox Formation evaporites 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 for more information).

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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 increasingly important role for 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. The current leading producers of vanadium are China, South Africa, and Russia, and these countries also hold the majority of global reserves. Vanadium's criticality is based on the U.S.'s 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 composition 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.

Vanadium in Utah

Utah's Colorado Plateau is home to many sandstone-hosted uranium and vanadium deposits (figure 29). These were originally mined for vanadium prior to the uranium boom in the 1940s and beyond. During the Atomic Energy Commission's procurement phase from 1947 to 1970, Utah produced an estimated 90 million lbs of vanadium metal, which would meet today's total domestic consumption for nearly five years. These sandstone-hosted deposits represent the primary domestic source for vanadium in the United States. As is the case for uranium mineralization, these deposits are hosted in fluvial sandstone lenses in the Triassic Chinle and Jurassic Morrison Formations, and vanadium is commonly found in the mineral carnotite (figure 33). Vanadium is most strongly enriched in the Salt Wash Member of the Morrison Formation and is associated with zones of increased organic material, such as carbonaceous plant detritus. The origin of these deposits is uncertain, though one common theory is that they came from the dissolution of iron- and titanium-oxide minerals in the Morrison Formation or other local source rocks. Vanadium had not been a primary target of modern exploration until recent higher vanadium prices renewed interest in the Colorado Plateau. Many of Utah's historical uranium districts were evaluated for their vanadium potential. The White Mesa Mill in Blanding has the capacity to process vanadium ore and produce high-purity "black flake" vanadium (figure 34), making the area particularly favorable for vanadium mining.

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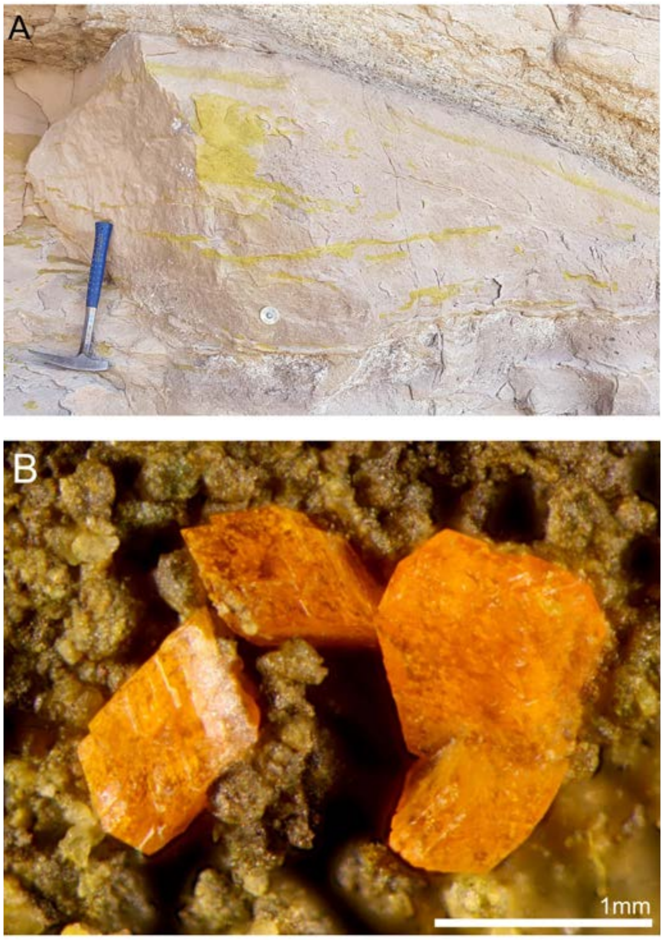

Figure 33. A. *Yellow carnotite mineralization roughly parallel to bedding in cross-bedded sandstone in the Temple Mountain mining district, Emery County.* ***B.*** *Crystals of orange lasalite, a vanadium-bearing mineral. Sample from the Vanadium Queen mine, where the mineral was first identified, in the La Sal mining district, which the mineral was named for, in San Juan County. Specimen and photo courtesy of Joe Marty.*

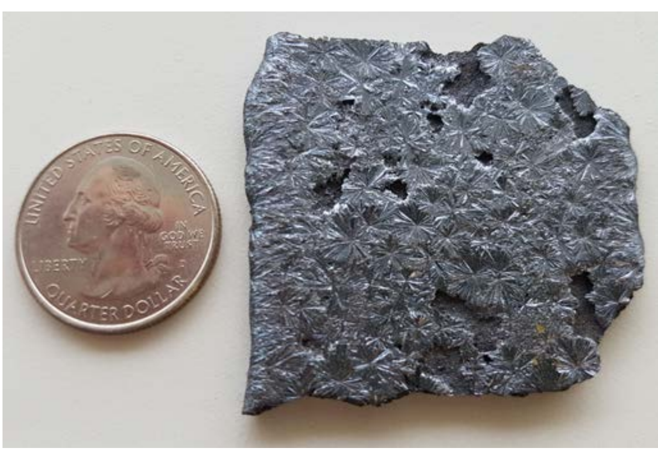

Figure 34. *Refined "black flake" vanadium produced from the White Mesa Mill in Blanding, Utah. Black flake vanadium is the high-purity vanadium end-product produced by the vanadium refinement circuit at the White Mesa Mill.*

POTENTIAL 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 35) associated with orogenic, magmatic-hydrothermal, and sediment-hosted mineralization make up most of the current antimony production globally.

The majority of antimony produced in Utah (figure 36) 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 with accessory realgar, orpiment, and fluorite. 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 Little Cottonwood district (vein and replacement-style silver-lead mineralization with byproduct antimony), and the Dry Lake Antimony mine in the Box Elder district (vein-hosted stibnite with associated silver). Antimony is an accessory element in sediment-hosted gold deposits such as Mercur and Gold Hill, though there are no records of antimony being produced from these districts.

Figure 35. *Stibnite from the Silver King Coalition mine in the Park City mining district, Summit County.*

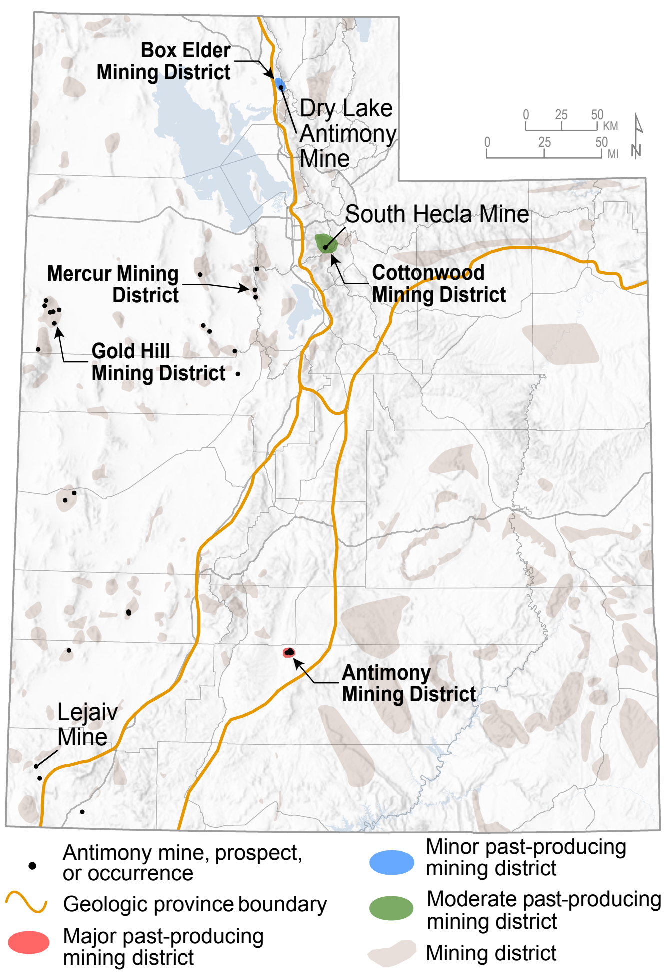

Figure 36. *Distribution of mining districts that have historically produced antimony and individual antimony prospects.*

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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-arsenide-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 has been Utah's premier arsenic producer (figure 37). Arsenopyrite was mined from polymetallic veins associated with Jurassic-age magmatism hosted in the Mississippian Ochre Mountain Limestone. Along with the arsenic, other metals such as copper, lead, silver, and gold were also mined from this type of deposit. 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 38).

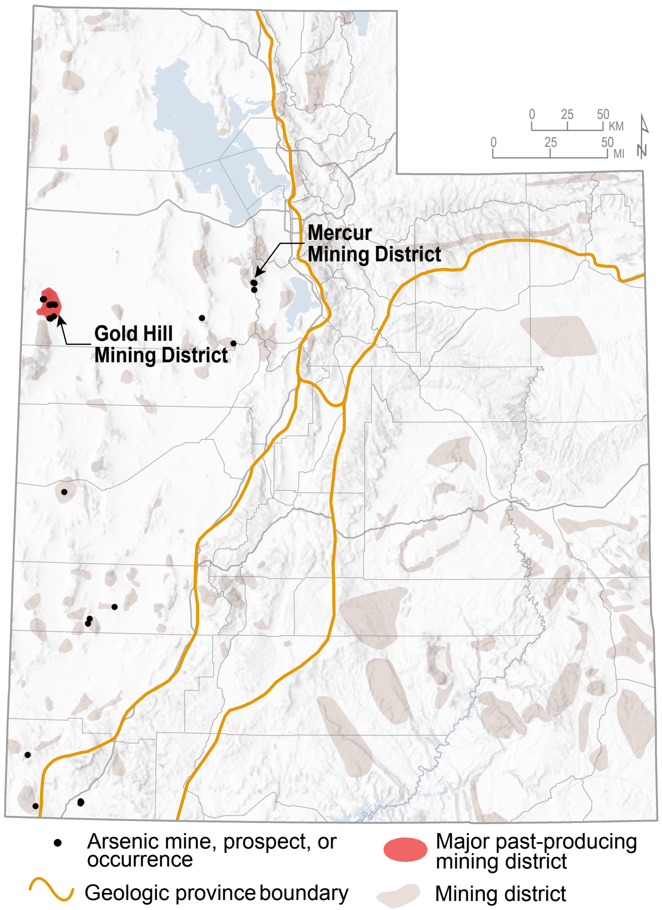

Figure 37. *Distribution of mining districts that have historically produced arsenic and individual arsenic prospects.*

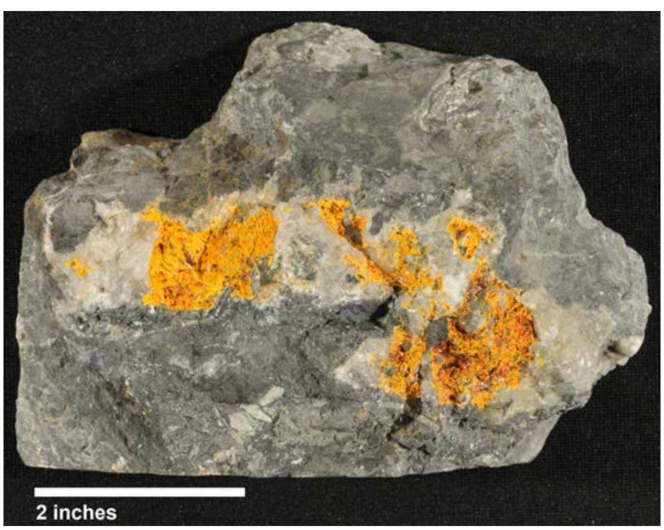

Figure 38. *Realgar (red) and orpiment (orange) from the Mercur mine, Mercur mining district, Tooele County.*

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 was therefore not closely monitored.

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Barite

Barite is a barium sulfate mineral ($BaSO_4$) that is useful because of its high density and inertness (figure 39). 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 2019, the United States imported 87% of the barite it consumed, providing justification for its criticality. Globally, China is the leading producer and supplied about 58% of the country's imported barite. Several countries, including China, 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 comes from bedded deposits in Nevada and residual deposits in Georgia.

Figure 39. *Bladed barite crystals from the Buckhorn Ag-Pb mine, Tooele County.*

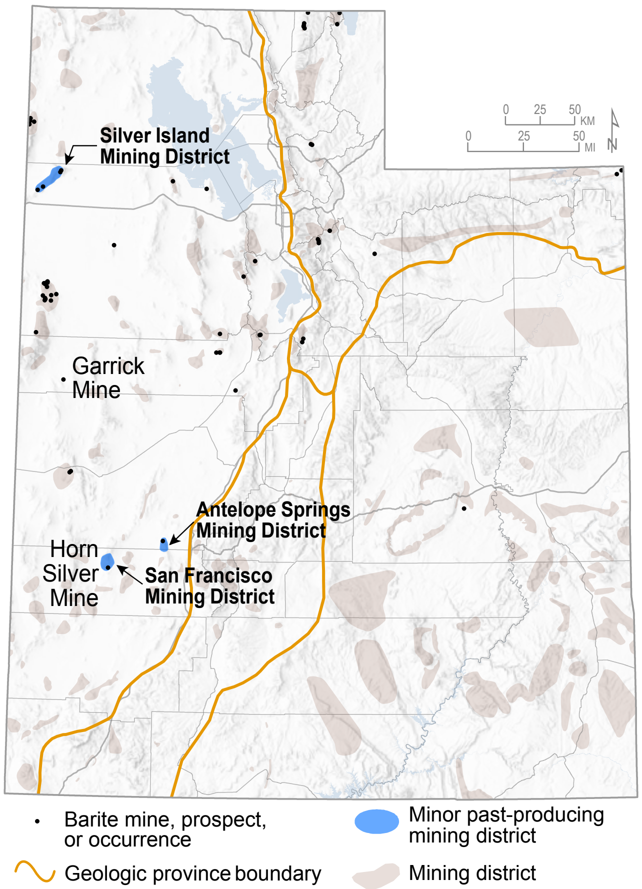

Figure 40. *Distribution of mining districts that have historically produced barite and individual barite prospects in Utah.*

Utah has produced a small amount of barite in Juab, Beaver, and Emery Counties (figure 40), but most of the production was from several decades ago, primarily the late 1950s and early 1960s. The largest historical producer, 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 whether any material was mined. Several small deposits, occurrences, and prospects exist across Utah, but none of the known deposits are significant enough to currently be considered economic under current conditions.

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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 41). 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

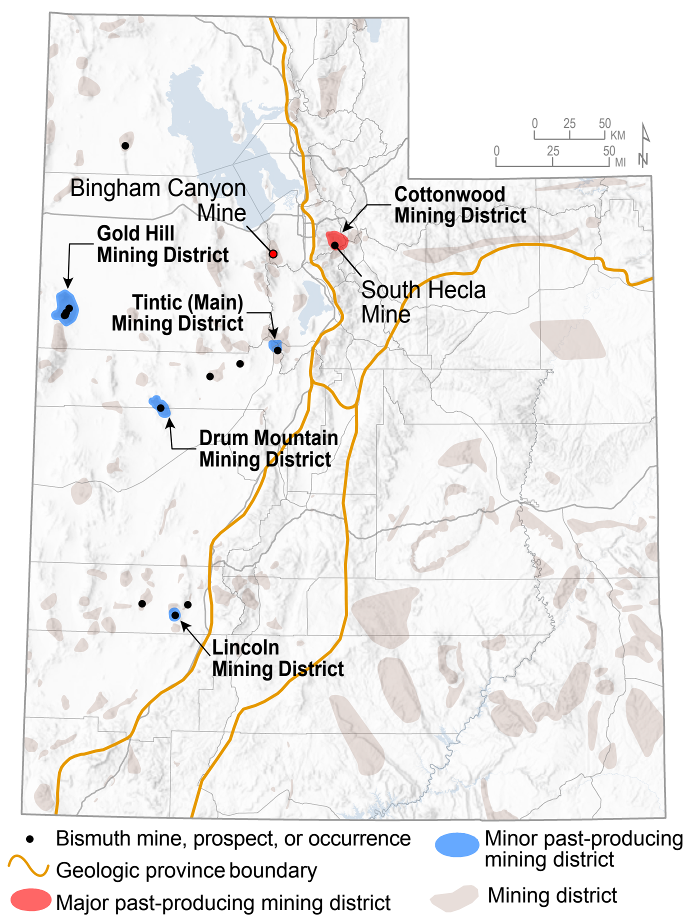

Figure 41. *Distribution of mining districts that have historically produced bismuth and individual bismuth prospects.*

producer of bismuth in Utah. Bismuthinite (Bi_2S_3, figure 42) 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, 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.

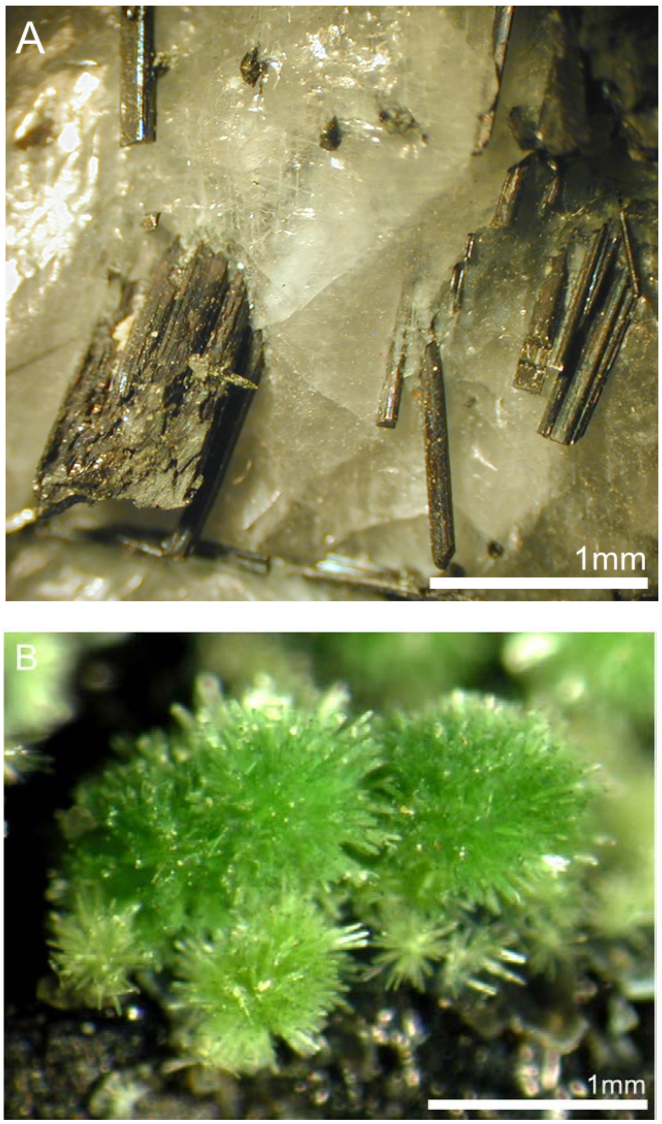

Figure 42. A. *Bismuthinite crystals hosted in calcite from the Creole mine in the Lincoln mining district, Beaver County. Specimen and photo courtesy of Dave W. Richardson.* ***B.*** *Green mixite, a bismuth-bearing mineral, from the Gold Hill mine in the Gold Hill mining district, Tooele County. Specimen and photo courtesy of Joe Marty.*

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Germanium and Gallium

Germanium is a metalloid, like arsenic and antimony, whereas gallium is a post-transition metal, like bismuth. Both elements have the unique characteristic of being denser as a liquid than as a solid, like ice and water. Germanium's uses are similar to indium's, in that it is an essential component in infrared optics, fiber-optic systems, and electronic and solar applications. Gallium is dominantly used in analog integrated circuits, and to a lesser extent LEDs, laser diodes, and digital integrated circuits. Both elements are important to a variety of high tech uses, green technology, and military applications. Germanium and gallium are grouped here because they are often recovered together as byproducts of base metal mining, particularly in the United States. Although germanium-bearing zinc concentrate is mined in Alaska, Tennessee, and Washington, the concentrates are exported for further processing. Hence, no primary refined germanium or gallium is produced domestically, and both are imported dominantly from China, supplemented by imports from multiple European countries.

The Apex mine located in Utah's Washington County produced copper, gallium, and germanium briefly from the late 1980s to early 1990s (figure 43). The Apex mine had previously been an intermittent copper and silver producer from 1884 to 1962, and the germanium and gallium was originally recognized in 1958. The germanium and gallium are hosted in iron minerals (hematite, goethite, jarosite; figure 44), and the deposit still contains a roughly estimated 660,000 lbs gallium, 1.7 million lbs germanium, and 36 million lbs copper. For context, this represents over 20 years of gallium and 26 years of germanium supply by current domestic consumption rates. However, the Apex mine has been reclaimed since the final period of mining in the 1990s, so near-term resumption of mining is unlikely.

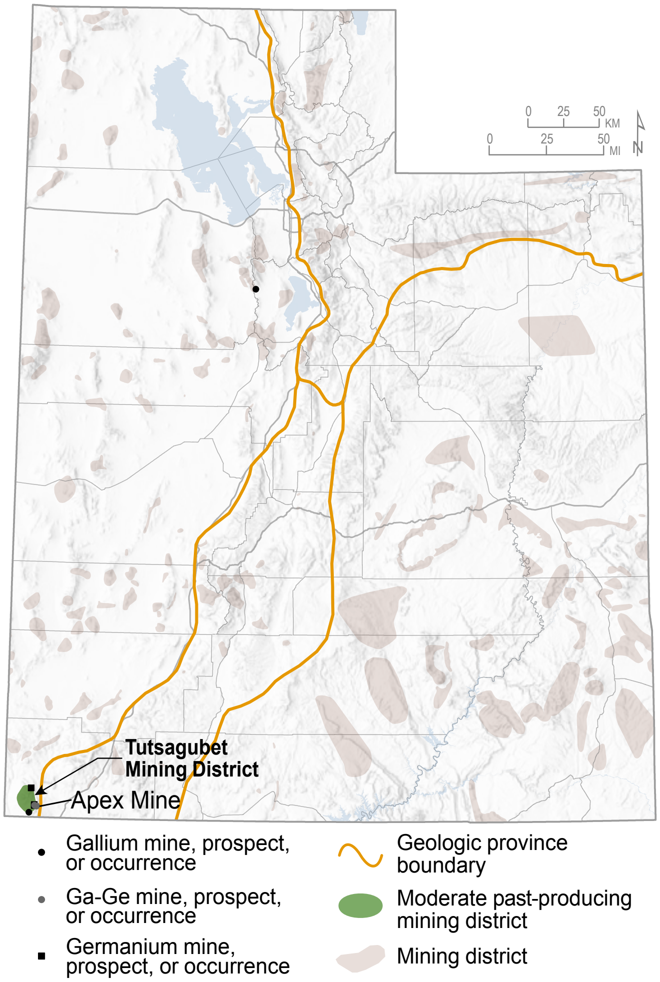

Figure 43. *Location of the Apex mine in the Tutsagubet mining district that has historically produced germanium and gallium and distribution of individual germanium and/or gallium prospects.*

Figure 44. *Hand sample of high-grade Ge-Ga plumbojarosite ore from the Apex mine in the Tutsagubet mining district, Washington County. Photo from Wenrich and Verbeek (2014), reproduced with the permission of Utah Geological Association.*

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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. Manganese is a fundamental element in modern industry, essential to iron-ore refining and 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 significantly from the Drum Mountain district in Juab and Millard Counties (figure 45). 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 re-

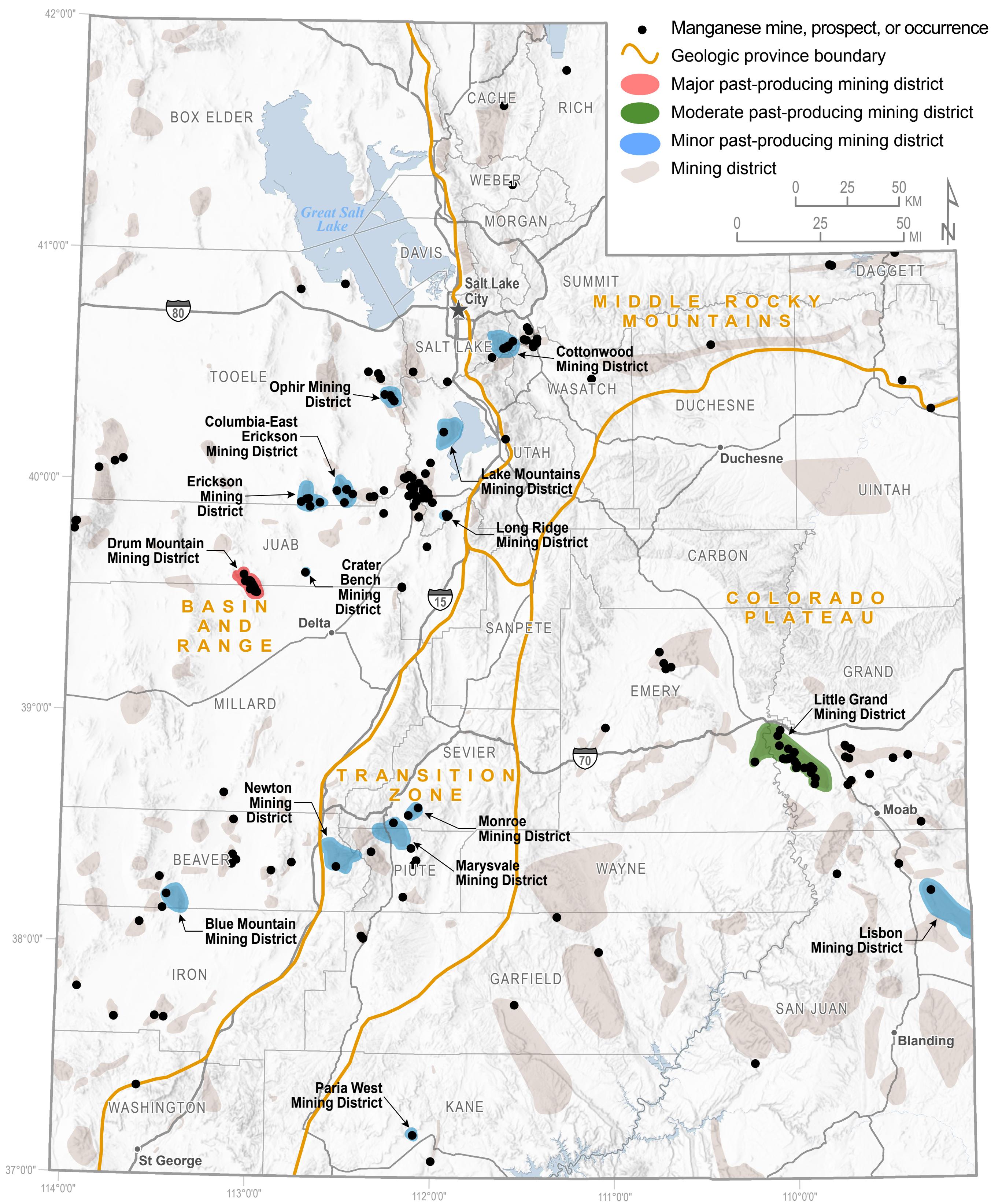

Figure 45. Distribution of mining districts that have historically produced manganese and individual manganese prospects.

Figure 46. *Replacement-style manganese mineralization from the Long Ridge manganese mining district in Utah County.*

placement 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 this style of replacement deposit (figure 46), and a number of districts have minor manganese production from replacement deposits in the eastern Basin and Range. However, the Little Grand district in the Colorado Plateau region was a notable manganese producer from sediment-hosted deposits. Manganese mineralization 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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Rare Earth Elements and Scandium

Rare earth elements, more commonly known as REEs, are a broad set of seventeen chemically and geologically similar elements. REEs include all fifteen 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. 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, geopolitical tensions and concerns over supply stability have caused other countries to seek to develop alternative REE sources. In the United States the Mountain Pass deposit in southeastern California is the only active rare earth mine. However, the United States does not yet have a REE processing facility, so these ores are sent to China for refining, although new REE processing plants are likely to be developed in the United States within the next five to ten years. Given the current domestic import reliance, the risk of supply disruption, and the widespread and specialty uses of rare earths, 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 several prospects have been identified (figure 47). Small amounts of scandium were produced from the Little Green Monster variscite deposit near the Lake Mountains in Utah County, where variscite ($AlPO_4{\cdot}2H_2O$,

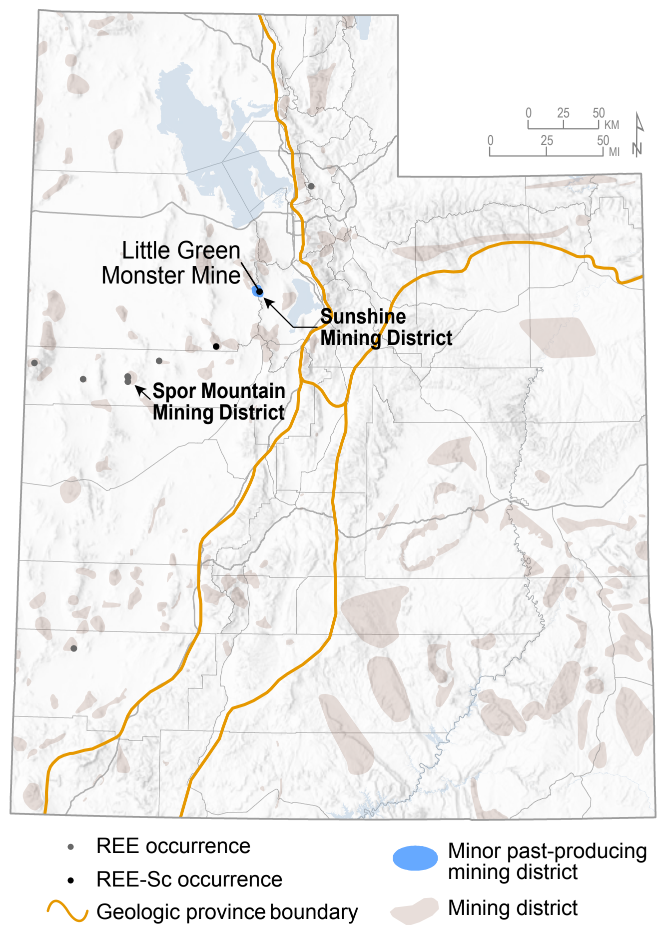

Figure 47. *Location of the Little Green Monster/Clay Canyon variscite and crandallite deposit in the Sunshine mining district in Tooele/Utah Counties that has historically produced scandium, and the distribution of REE ± scandium prospects.*

Figure 48. Variscite sample from the Little Green Monster/Clay Canyon variscite and crandallite deposit in the Sunshine mining district, Tooele/Utah Counties.

figure 48) and crandallite ($CaAl_3(PO_4)_2(OH)_5 \cdot H_2O$) contained 0.01 to 0.8 wt. % scandium oxide (Sc_2O_3). The Beryllium Belt (figure 7) has evolved chemistry of the type favorable to rare earth enrichment and limited geochemical work has shown that the Spor Mountain tailings may be enriched in REEs, which could be recovered as a byproduct of the beryllium mining. Other potential sources of REEs in Utah include phosphate deposits and iron apatite deposits, but there has been little research on the potential of these areas.

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Tellurium

Tellurium, a metalloid like arsenic, antimony, and germanium, is a rare chalcophile element, meaning it readily bonds with sulfur to form sulfide minerals. The main use for tellurium is for cadmium-telluride film used in solar cells. In addition to photovoltaic applications, tellurium is also used in thermoelectric products and as a metallurgical additive to improve performance of various alloys. Like rhenium, most tellurium (as much as 90% globally) is recovered as a byproduct from porphyry copper mining. Telluride minerals also form in 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. The only two active primary tellurium deposits globally are epithermal deposits located in China and Finland.

In Utah, tellurium has been produced as a byproduct of the copper mining at the Bingham Canyon porphyry deposit (figures 14 and 49). Tellurium is associated with the copper

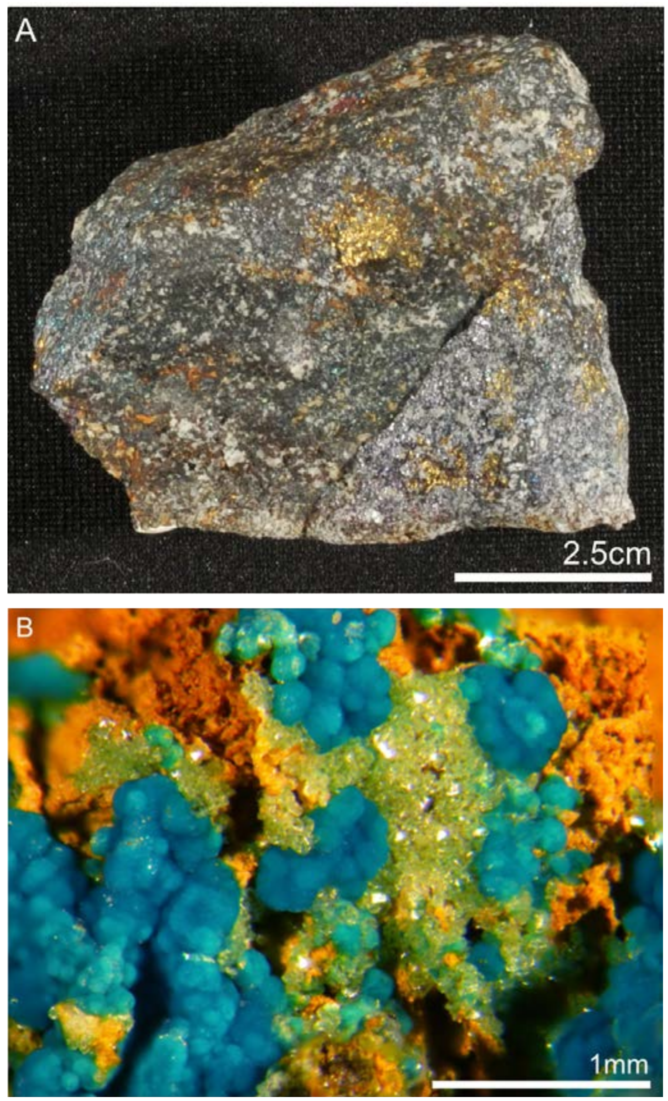

Figure 49. A. *High-grade copper ore from the Bingham Canyon copper mine. Tellurium is present at very low concentrations in the copper ore and can be isolated during the copper refinement process.* ***B.*** *Blue eurekadumpite with yellow-green dugganite, both tellurium-bearing minerals, from the Gold Chain mine in the Tintic mining district, Juab County. Specimen and photo courtesy of Joe Marty.*

refining process and is concentrated in the anode slimes that are produced in the final step of copper refinement, when the copper anode is dissolved and redeposited as pure copper on a stainless steel cathode in an electrolytic bath. All impurities such as gold, silver, platinum, palladium, and tellurium in the copper anode are left behind. It is difficult to obtain numbers for specific tellurium production, because Bingham currently does not refine the anode slimes to recover tellurium. However, tellurium was recovered in the past and Bingham may have the capability to begin producing refined tellurium again, should market economics prove favorable.

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Tungsten

Tungsten is a dense metal with the highest melting point of any metal, and 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 ($CaWO_4$, figure 50) and wolframite ($FeWO_4$). Tungsten deposits are almost exclusively associated with felsic intrusives, and tungsten mineralization can result from contact metamorphism and alteration (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 (figure 51). 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 (this represents less than 1% of imported tungsten concentrates in 2019). The mine has not been in operation since. The tungsten mineralization at Gold Hill is associated with skarn and breccia bodies around a Jurassic granodiorite and an Eocene quartz monzonite, both intruding Paleozoic marine sequences. In Gold Hill and in other tungsten districts in Utah such as Notch Peak and Granite, the majority of tungsten production was during WWII. Utah could potentially see limited tungsten mining restarted given favorable economics.

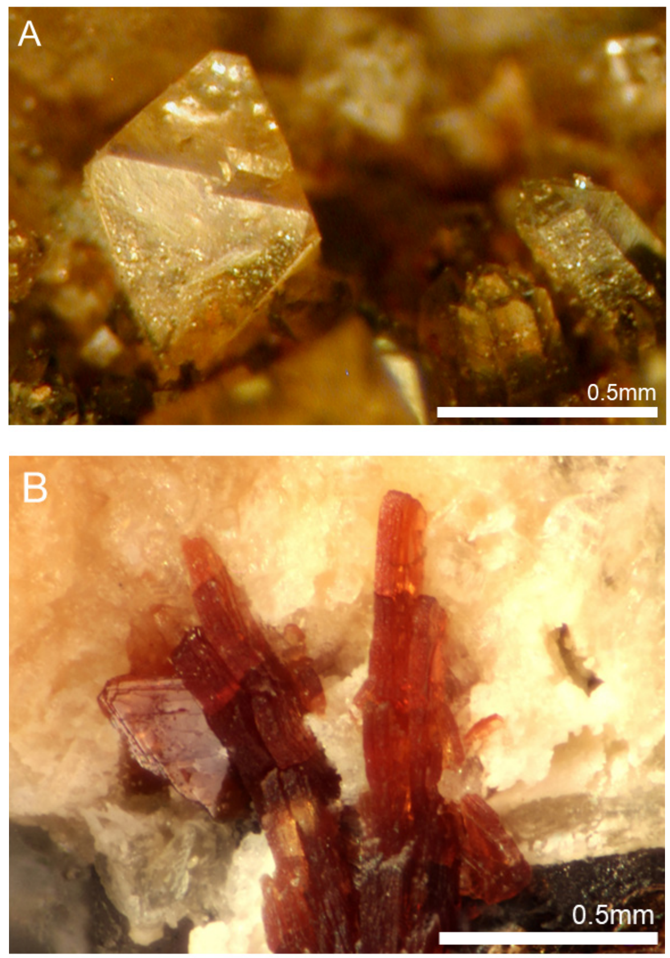

Figure 50. A. *Scheelite crystal with quartz hosted in calcite from the Ophir mine in the Ophir mining district, Tooele County. Specimen and photo courtesy of Dave W. Richardson.* ***B.*** *Red-brown crystals of ophirite, a tungsten-bearing mineral discovered and named for the Ophir mine in the Ophir mining district, Tooele County. Specimen and photo courtesy of Joe Marty.*

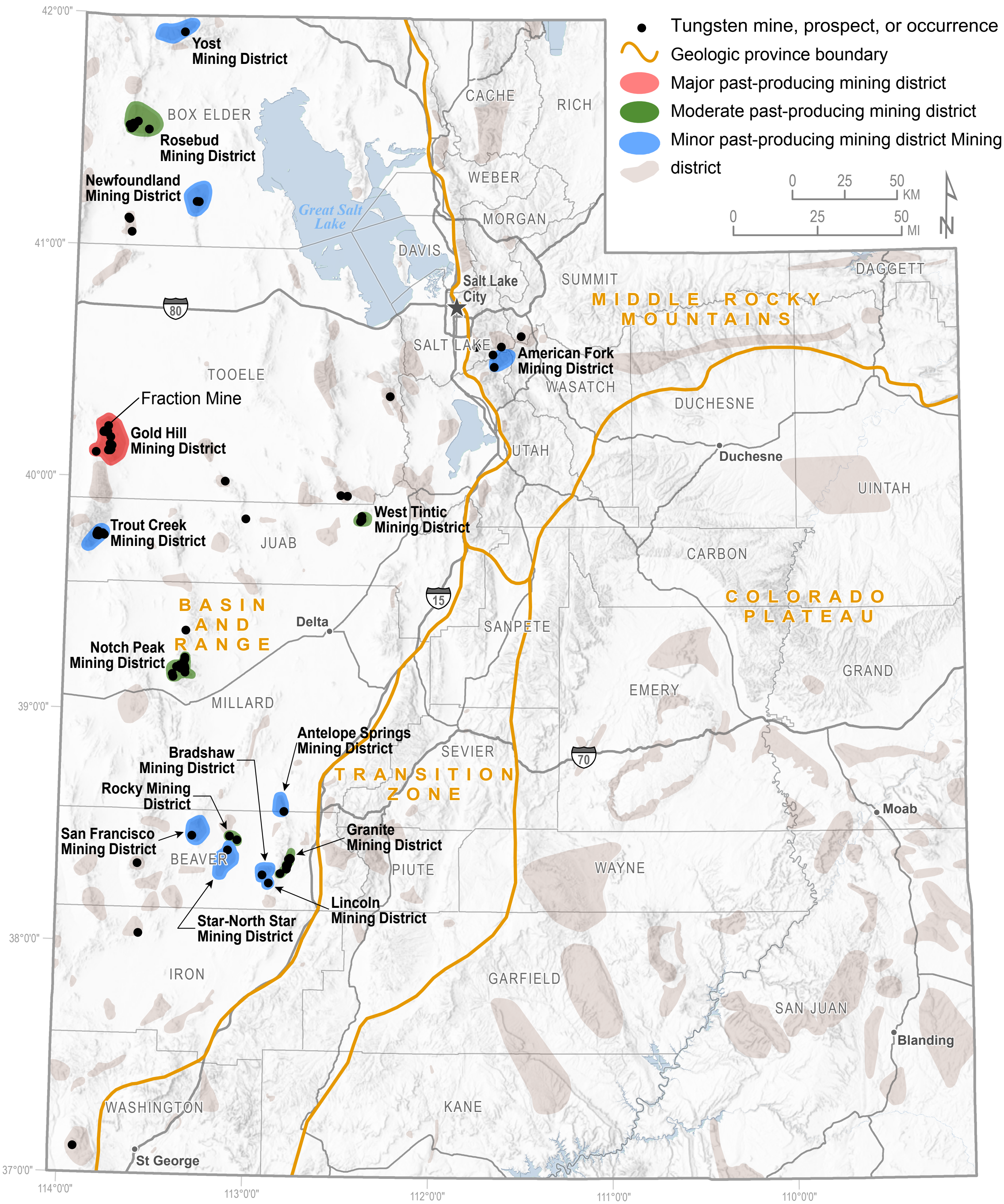

Figure 51. Distribution of mining districts that have historically produced tungsten and individual tungsten prospects.

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MINOR 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 when combined with silica. 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/or 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 52), where cobalt can occur in values up to a few weight percent. The Colt Mesa deposit in Garfield County has recently been evaluated for cobalt potential, and sediment-hosted copper projects such as Copper Ridge in Grand County are also considering cobalt grades as potential support for project economics. Other minor occurrences include polymetallic veins in base metal districts (e.g., Big Cottonwood district) and deposits associated with iron mineralization in the southern Uinta Mountains. 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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Tin

Tin, which takes its element symbol Sn from the Latin name *stannum*, has a history dating back more than 5000 years 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 as early as 3500 B.C., and its discovery 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 by aluminum. Currently tin is a diverse metal used in a variety of applications including tinplate for steel containers, construction materials, alloys and solders, 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 alteration, 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 52). 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 tin production economic.

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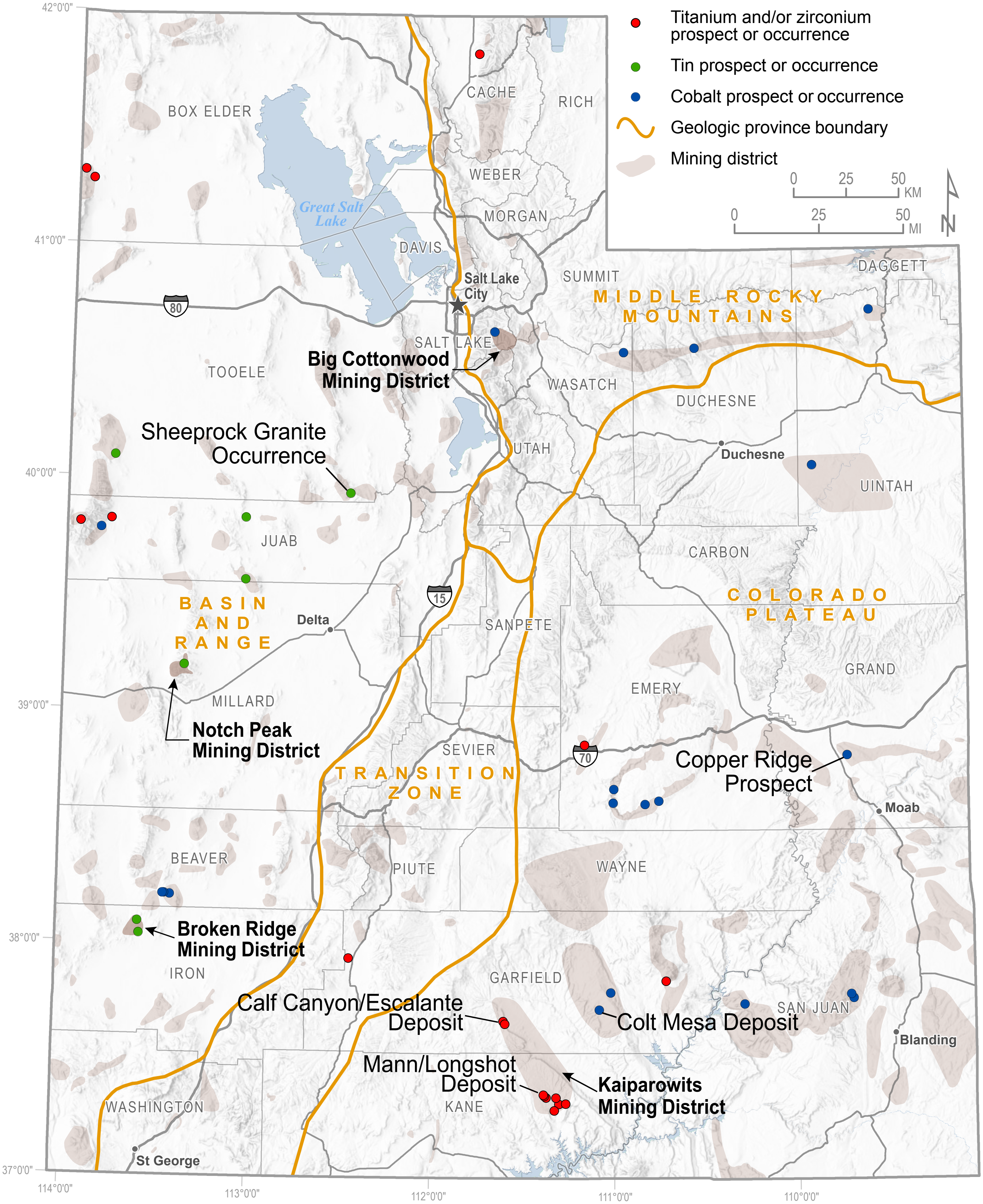

***Figure 52.** Distribution of cobalt, tin, titanium, and zirconium/hafnium occurrences in Utah.*

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 applications. 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 (over 90%). The United States has recently become an exporter of zirconium ores and concentrates; however, zirconium and hafnium are still considered critical due to the essential nature of their applications.

These critical minerals are grouped together because they are most often extracted from the same type of deposit, 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 Canada, China, Australia, Mozambique, South Africa, and others, but Australia and China 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 comes from deposits in Georgia and Florida.

Utah has not produced 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 52). These deposits were discovered in the 1950s and have been staked, evaluated, and abandoned multiple times. 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, Niobium and Tantalum, Other PGEs, Strontium

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 occurrences, such as magmatic sulfide depos-its or carbonatites, that do not exist in our 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 min-eral 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 or current 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 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 53), but there are no known occurrences of significant graphite development.

Figure 53. *Carbon-rich layer in the lower Green River Formation. Utah has notable carbon-rich sedimentary units and coal deposits, but none have been thermally metamorphosed to graphite. Photo courtesy of Ryan Gall.*

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 cell phones and in super alloys for jet engines. Although Utah hosts some alkaline intrusives and pegmatites, no niobium or tantalum minerals (pyrochlore ($(Na,Ca)_2Nb_2O_6(OH,F)$) and tantalite ($(Fe, Mn)(Ta, Nb)_2O_6$), respectively) 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. The primary source of PGEs globally are from bodies of mafic to ultramafic magmas that have become saturated with sulfur and produced an immiscible metal-rich sulfide liquid. These types of deposits are associated with large igneous provinces (LIPs), which are not known to exist in Utah.

Strontium is most commonly found as celestine ($SrSO_4$), which is used in drilling muds by the petroleum industry and hence is sensitive to fluctuations in the oil and gas markets. It can also occur as the strontium carbonate mineral strontianite ($SrCO_3$), from which strontium is extracted for a variety of industrial and chemical applications including permanent magnets, pyrotechnics, and alloys. The United States produces no primary strontium, having last mined strontianite in 2006. Utah hosts minor occurrences of celestine (figure 54), as it is a relatively common gangue mineral in sediment-hosted manganese and uranium deposits, barite vein deposits, and Mississippi Valley-type lead-zinc deposits. However, these occurrences are extremely minor in comparison to what would be required for an economic deposit and do not represent a realistic strontium resource.

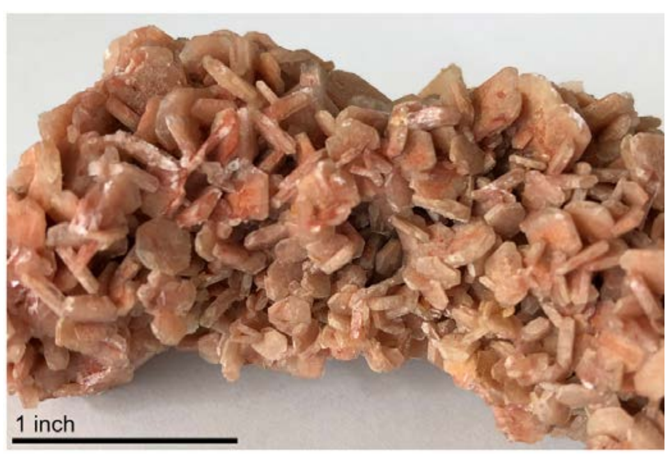

Figure 54. *Celestite, also known as celestine, from the San Rafael Swell mining district in Emery County.*

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