Beryllium—A Critical Mineral Commodity—Resources, Production, and Supply Chain

Beryllium is a lightweight metallic element used in a wide variety of specialty and industrial applications. As a function of its unique chemical and physical properties, such as a high stiffness-to-weight ratio, resistance to temperature extremes, and high thermal conductivity, beryllium cannot be easily replaced by substitute materials in applications where combinations of these properties make it the material of choice. Because the number of beryllium producers is limited and the use of substitute materials in specific defense-related applications that are vital to *national security* is inadequate, several studies have categorized beryllium as a critical and strategic material (National Research Council, 2008, p. 170). This categorization has led to the United States Government recommending that beryllium be stockpiled for use in the event of a national emergency (U.S. Department of Defense, 2015, p. 3). As of December 31, 2015, the National Defense Stockpile inventory of hot-pressed beryllium metal powder, structured beryllium metal powder, and vacuum-cast beryllium metal totaled 78 metric tons (t).

The U.S. Geological Survey (USGS) Mineral Resources Program supports research on the occurrence, quality, quantity, and availability of mineral resources vital to the economy and national security. The USGS, through its National Minerals Information Center (NMIC), collects, analyzes, and disseminates information on more than 90 nonfuel mineral commodities from more than 180 countries. This fact sheet provides information on the production, consumption, supply chain, geology, and resource availability of beryllium in a global context.

Global Beryllium Production

Beryllium is currently produced from two minerals: bertrandite ($Be_4Si_2O_7(OH)_2$) and beryl ($Be_3Al_2Si_6O_{18}$). Bertrandite, which contains about 15 weight percent beryllium, is the principal beryllium mineral mined in the United States. Bertrandite ore mined in the United States contains less than 0.5 weight percent beryllium. Beryl, which can contain up to 5 weight percent beryllium, is the principal beryllium mineral mined in the rest of the world; beryl ore typically contains from 2 to 4 weight percent beryllium. Countries with active industrial beryl mining operations include Brazil, China, Madagascar, Mozambique, Nigeria, Portugal, and Rwanda. From a historical perspective, Argentina, India, and several countries in sub-Saharan Africa were once prominent producers of beryl ore (fig. 1). Other nations that produce gemstone beryl, such as Zambia, may also have produced industrial beryl ore. The United States produced an estimated 90 percent of the world's beryllium in 2015.

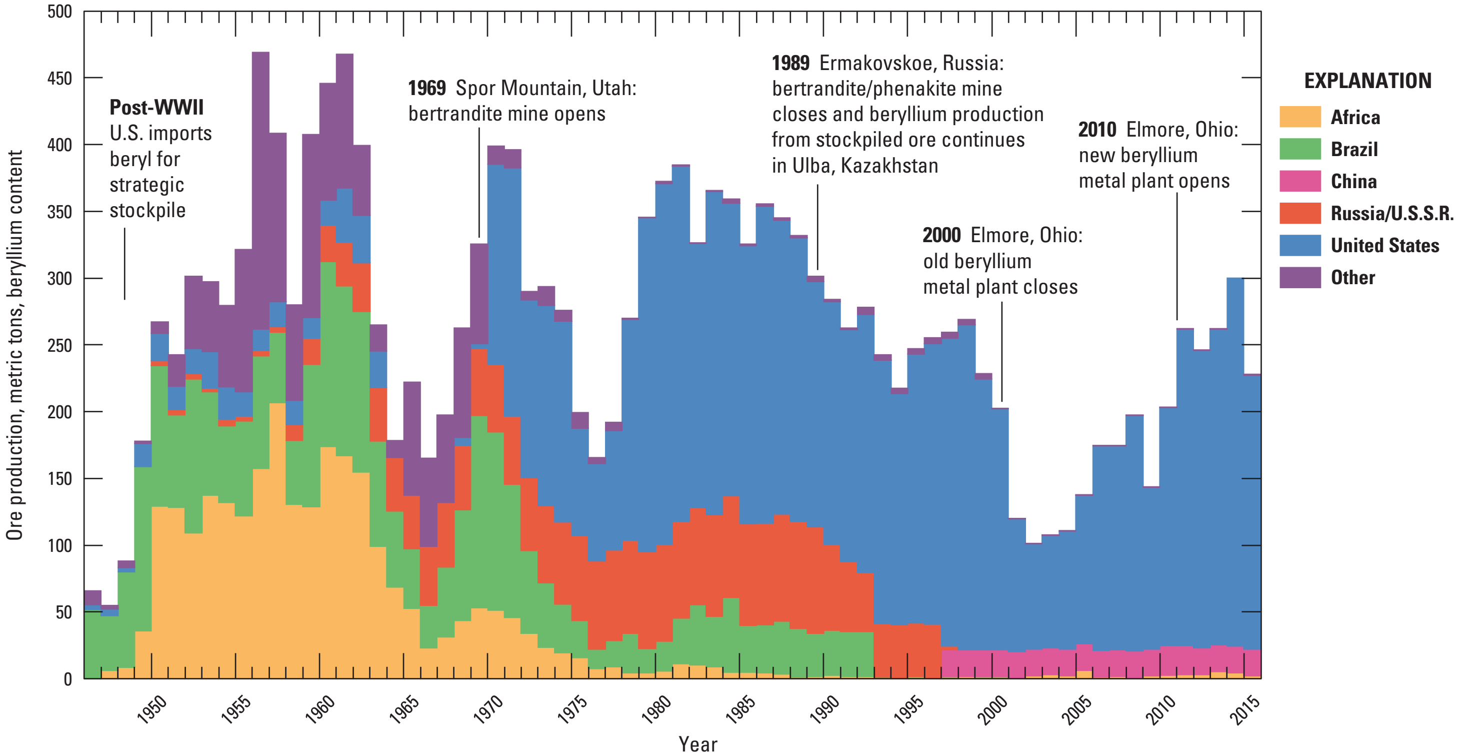

Figure 1. Trends in beryllium mine production from 1946 through 2015 illustrate the dominance of United States production since the opening of the Spor Mountain, Utah, bertrandite mine in 1969. With the exception of Spor Mountain and Ermakovskoe, Russia, beryllium production was derived from beryl mined from pegmatite deposits.

The United States, Kazakhstan, and China are the only countries known to process beryllium ores and concentrates into beryllium products. Materion Corporation is the sole producer of beryllium ore in the United States. Materion processes imported beryl ore, alongside bertrandite ore from open pit mines in the Spor Mountain region of Juab County, Utah, into beryllium hydroxide at their mill near Delta, Utah. The processed beryllium hydroxide is then either shipped to Elmore, Ohio, where Materion converts it into metal, beryllium-copper master alloy, and oxide, or it is sold to producers of other beryllium products. In 2015, U.S. mine shipments of beryllium ore were estimated to contain 205 t of beryllium. From 2005 to 2014, U.S. mine shipments of beryllium ore increased at an average rate of 10 percent per year.

Kazakhstan's Ulba Metallurgical Plant, a subsidiary of National Atomic Company Kazatomprom JSC, reportedly produces beryllium hydroxide from stockpiled concentrate previously extracted from the Ermakovskoe beryllium deposit in Russia. The concentrate stockpile was accumulated by 1992, before the breakup of the Soviet Union, and was estimated, in 2002, to hold a 20-year supply (Levine and Wallace, 2004, p. 6.16); consistent with this estimation, anecdotal reports from 2015 suggest that only a few years' worth of beryllium concentrate remain in the stockpile. Also in 2015, it was estimated that the Ulba Metallurgical Plant produced about 90 t of beryllium contained in beryllium-copper alloys, beryllium oxide ceramics, and beryllium metal.

China's Shuikoushan Non-Ferrous Metals Group Co., Ltd. processes beryllium ores to produce beryllium products in various forms at its refinery in Songbai, Hunan Province. The plant has an estimated production capacity of 150 metric tons per year (t/yr) of beryllium oxide (36 weight percent beryllium) and an estimated production capacity of 1,500 t/yr of beryllium-copper master alloy (typically containing 4 weight percent beryllium). Fuyun Hengsheng Beryllium Industry Co., Ltd.'s refinery, located in Fuyun in the northwest section of the Xinjiang Uygur Autonomous Region, was designed to produce 100 t/yr of beryllium oxide and 800 t/yr of beryllium-copper master alloy. Estimates in 2015 indicated that China produced about 65 t of beryllium contained in beryllium-copper alloys, beryllium oxide ceramics, and beryllium metal at these two plants. Approximately 20 t of the contained beryllium was produced from domestic ore, and 45 t was derived from foreign sources, most likely Kazakhstan's Ulba Metallurgical Plant.

Anticipated increases in the demand for beryllium have led Russia to resume bertrandite mining and construct a processing plant at the Ermakovskoe beryllium deposit in the Republic of Buryatiya in eastern Siberia. The new plant is expected to produce beryllium hydroxide for export to the Ulba Metallurgical Plant in Kazakhstan, and to China and Japan, for processing into beryllium metal and beryllium alloys. The annual mining and processing capacities are estimated to be 25,000 t/yr of bertrandite ore and 130 t/yr of beryllium hydroxide. Russia, in 2015, announced that it intended to produce beryllium metal on a commercial scale by 2020.

U.S. Beryllium Consumption

In 2015, reported U.S. consumption of bertrandite and beryl ore for the production of beryllium hydroxide was approximately 220 t of contained beryllium. From 2005 to 2014, reported U.S. bertrandite and beryl ore consumption increased at an average rate of about 6 percent per year. U.S. apparent consumption of all beryllium materials in 2015, as calculated from mine shipments, net trade, and changes in Government and industry stocks, was estimated to be about 233 t of contained beryllium. Based on the estimated unit value of beryllium in imported beryllium-copper master alloy, the 233 t was valued at about $119 million. Based on value-added sales revenues, approximately 20 percent of beryllium products were used in industrial components, 18 percent in consumer electronics, 16 percent in automotive electronics, 11 percent in defense applications, 8 percent in telecommunications infrastructure, 7 percent in energy applications, 2 percent in medical applications, and 18 percent in other applications (fig. 2; Materion Corporation, 2016). Beryllium alloy strip and bulk products, the most common forms of processed beryllium, were used in all application areas. The majority of unalloyed beryllium metal and beryllium composite products were used in defense and scientific applications.

Beryllium Supply Chain

Beryllium occurs in a variety of intermediate materials as it moves through industrial stages including mining, processing, manufacturing, and end use (fig. 2). Although 90 percent of current beryllium production is derived from bertrandite ore, with the remainder derived from beryl ore, the distribution between source materials can vary depending on the relative availability of source materials. Before the opening of the Spor Mountain, Utah, bertrandite mine in 1969, nearly all primary beryllium was produced from beryl mined from pegmatites and sorted by hand. Extracting beryllium from bertrandite ore involves

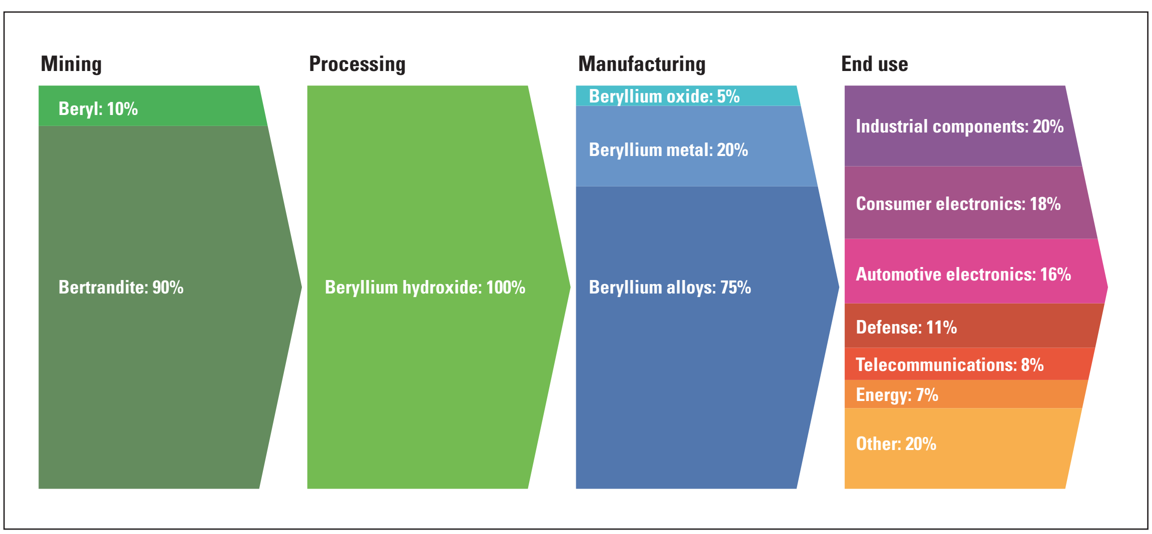

Figure 2. Simplified flow diagram of the beryllium industry. Percentages are relative to the total beryllium flow at each stage; flows between stages do not account for losses, changes in stocks, or recycling. End use category labelled "Other" includes 2 percent used in medical applications (Materion Corporation, 2016).

crushing, grinding, and leaching with sulfuric acid. By contrast, processing beryl ore involves multiple steps, including crushing, heating beryl to its melting point of 1,650 °C, rapidly quenching the melt in water to produce a glass or "frit," reheating the frit to about 1,000 °C, grinding, and leaching the partially devitrified frit with sulfuric acid. Impurities such as iron and aluminum are removed from the beryllium sulfate leach solutions by solvent extraction. About 87 percent of the beryllium content of bertrandite and beryl ores is recovered in the form of beryllium hydroxide and shipped to producers of beryllium products, while the remaining insoluble beryllium is not recovered and is sent to tailings ponds at the mill site.

Beryllium hydroxide is predominantly used in the production of beryllium-copper master alloys and, to a lesser extent, beryllium-nickel and beryllium-aluminum alloys. Beryllium-copper master alloys contain about 4 weight percent beryllium and are diluted with pure copper to produce different compositions ranging from 0.15 to 2 weight percent beryllium, depending on the strength and electrical conductivity required for specific applications. Alloys with low (<2 weight percent) beryllium content account for about 75 percent of global beryllium consumption, whereas pure (>99 weight percent) beryllium metal and composites with high (>60 weight percent) beryllium content account for 20 percent of consumption. Beryllium oxide ceramics account for the remaining 5 percent of consumption (Trueman and Sabey, 2014).

Beryllium scrap is generated and recovered at various stages of production. Scrap generated during the manufacture of beryllium metals and alloys, and during the fabrication of beryllium products, is known as process scrap or "new" scrap. New scrap is recovered and returned to metal and alloy manufacturers. Beryllium materials contained within products that reach the end of their useful life constitute postconsumer scrap or "old" scrap. Disassembling and processing old scrap are economically viable processes only for large volumes of materials with high beryllium content, such as military aircraft parts and products used in the aerospace industry. Alloys with low beryllium content are lost to the beryllium industry because they are recycled with the host metal or are lost to slag during smelting. Because of these dissipative losses, the majority of postconsumer beryllium is too widely dispersed or highly diluted to be economically recovered at present. Significant losses also occur as a result of use in space and military applications. Quantitative estimates of beryllium recycling rates are the focus of ongoing materials flow analysis by the U.S. Geological Survey, but recycling is excluded from figure 2 because of the wide range in previously reported values (Trueman and Sabey, 2014).

Geology and Resource Availability

Beryllium, the lightest of the alkaline earth elements, has an atomic number of 4. As a consequence of its small ionic radius (about 0.27 angstroms), beryllium atoms bond strongly to other atoms, forming compounds with great hardness and high melting temperatures. Because of its small ionic radius and charge, beryllium does not easily substitute for other elements commonly found in rock-forming minerals; similarly, beryllium is not easily displaced by other elements in crystals and tends to form distinct minerals.

Although more than 100 minerals containing beryllium are known to occur in nature, most are rare or found in a small number of unique localities. The three most common beryllium-bearing minerals found in economic deposits are beryl, bertrandite, and phenakite (Be_2SiO_4). Beryl is the main beryllium mineral in igneous intrusions and metamorphic rocks formed at moderate to high temperatures. Bertrandite and phenakite are the predominant ore minerals formed at moderate to low temperatures. Beryllium deposits are found in certain geologic settings and are typically associated with specialized rock types. These include peralkaline granite- and pegmatite-related deposits that contain beryl and phenakite in high-grade pockets or seams and in the gravels formed by the weathering of such rocks; high-temperature skarn and greisen deposits containing beryl and phenakite related to specialized granitic intrusions; and low-temperature epithermal deposits that mainly contain bertrandite and are related to volcanic rocks. Estimates of ore grade and tonnage for a variety of beryllium deposits, districts, and belts in the United States, and worldwide, are shown in figure 3.

Although many intrusive igneous rocks, such as granite, syenite, and gabbro, can contain minor amounts of beryl, only rare-metal granitic pegmatites of the lithium-cesium-tantalum (LCT) type and gravel deposits formed by the weathering of LCT pegmatites contain beryl in sufficient quantities to mine. Beryl in zoned, rare-metal pegmatites can occur with other minerals

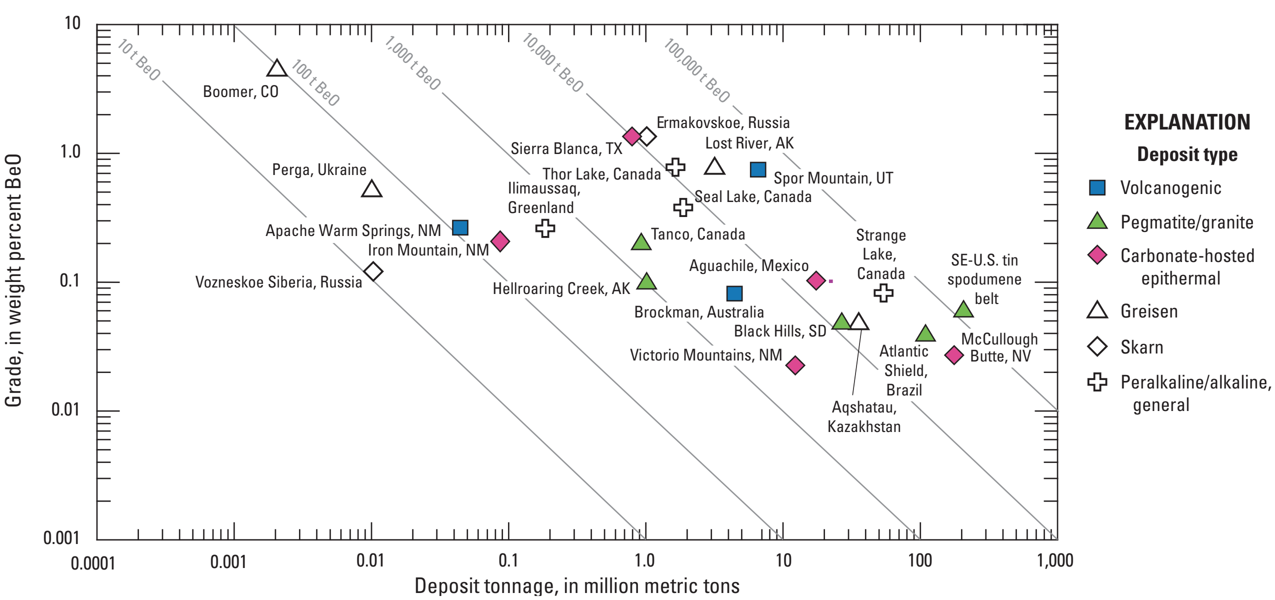

Figure 3. Estimates of grade and tonnage for a variety of beryllium deposits, districts, and belts in the United States and worldwide that have potential for minable beryllium resources. Diagonal lines show equal value of contained metal in metric tons. Available data for deposits of these types are sparse; some deposit information was compiled using incompletely documented past-production, reserve, and resource information. (For additional information, see Trueman and Sabey [2014]; Foley and others [in press], and references therein.)

containing commodities of commercial importance, such as cesium, lithium, and tantalum, as well as clay minerals, feldspar, muscovite, and high-purity quartz. Beryl-bearing pegmatite districts occur in Brazil, Canada, China, Mozambique, Namibia, Portugal, and Zimbabwe. Deposits in the United States that were mined historically include pegmatite bodies in Colorado, Maine, New Hampshire, New Mexico, North Carolina, and South Dakota. For example, pegmatites at the Palermo No. 1 Mine, Grafton County, New Hampshire, produced much of the beryllium metal used for the Manhattan Project during World War II.

Non-pegmatite-related volcanogenic deposits form in a comparatively unusual geologic setting where bertrandite and other minerals replace carbonate clasts entrained as rock fragments in beryllium-rich tuff units. The Spor Mountain deposits of Utah (fig. 4) make up the only known economic example of this deposit type. Mineralized tuff at Spor Mountain contains pore fillings, veinlets, and ore nodules filled with bertrandite, opal, fluorite, manganese oxides, clay minerals, and secondary uranium minerals. Original resource and grade estimates for Spor Mountain completed before 1969 suggest that the eight known orebodies, in total, exceeded 10 million metric tons, grading almost 1 weight percent beryllium oxide (fig. 3). In the early years of production, ore nodules containing up to 2 to 3 weight percent beryllium were not uncommon. More recent estimates indicate 9.6 million metric tons grading 0.7 weight percent beryllium oxide, with an estimated 70-year supply of beryllium in proven reserves remaining at Spor Mountain at current rates of production (Materion Corporation, 2016). As individual deposits are mined out, overall grades might be lowered below current cutoff values. Volcanic rocks at Spor Mountain also contain other mineral commodities of commercial importance including fluorite, lithium, and uranium (Foley and others, in press, and references therein).

Non-pegmatite skarn deposits form where beryllium-rich igneous rocks intrude and alter carbonate host rock sequences. These deposits can contain varying amounts of bertrandite and phenakite. For example, at the Ermakovskoe beryllium deposit in Russia (fig. 3), bertrandite and phenakite formed as replacement minerals within a large block, or roof pendant, of shattered limestone within a gabbro intruded by a peralkaline granite stock (Foley and others, in press, and references therein).

Beryllium Resources and Future Supply

The United States currently meets most of its beryllium requirements from domestic sources of bertrandite and imports of beryl. Approximately 65 percent of the estimated global resources of non-pegmatitic beryllium are located in the United States. In addition to the bertrandite reserves remaining at Spor Mountain, Utah, beryllium resources in Alaska, New Mexico, and Texas are undergoing economic feasibility analysis. Recovery of beryllium materials through scrap processing and recycling constitutes a potentially significant source of secondary production.

USGS scientists are currently investigating how and where beryllium resources are concentrated in the Earth's crust and how beryllium materials circulate through industrial processes. This knowledge can be used to assess the mineral resources of the United States, to establish the likely availability of future domestic beryllium supplies, and to further understand the interplay among beryllium production, consumption, and recycling. Methodologies developed by the USGS to assess global mineral resources and supply-chain dynamics help support the stewardship of Federal lands and inform U.S. Government policymakers.

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Figure 4. The Fluro Pit of the Spor Mountain, Utah, bertrandite mine—view to the west. Height of opposite wall is approximately 50 m.

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