USGS critical minerals review

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The United States' supply of critical minerals has been a concern and a source of potential strategic vulnerabilities for U.S. economic and national security interests for decades (for example, see Strategic and Critical Minerals Stockpiling Act, 1939). More recently, with the rapid increase in the types of materials being used in advanced technologies (Fortier et al. 2018a), and geopolitical events surrounding the supply of rare earth elements (Ting and Seaman, 2013), among other developments, the critical minerals issue has again achieved a high level of visibility within the U.S. government (Executive Order 13817 (2017)).

In this paper, the U.S. Geological Survey (USGS) provides an overview of its ongoing focus on critical minerals through the agency's core competencies in mineral information, mineral resource assessments, geologic and topographic mapping, geophysical surveys and mineral resource research. Aspects of the multifaceted critical minerals issue addressed here include:

- Identifying minerals that meet the definition of "critical" provided in Executive Order 13817.
- U.S. net import reliance for critical mineral raw materials.
- Current status of domestic critical mineral resource assessments.
- Current status of topographic and geologic mapping, and geophysical survey coverage of the United States.
- The Earth Mapping Resources Initiative (Earth MRI) to support future critical mineral exploration.
- Critical mineral potential of waste streams from extractive industries.

Identifying minerals as critical

U.S. government agencies and other organizations use a number of existing definitions and criteria to identify a mineral or mineral material as critical, strategic or otherwise important. The executive order defined a "critical mineral" to be "(i) a nonfuel mineral or mineral material essential to the economic and national security of the United States, (ii) the supply chain of which is vulnerable to disruption, and (iii) that serves an essential function in the manufacturing of a product, the absence of which would have significant consequences for our economy and national security." This definition is broadly consistent with that defined by the National Research Council (NRC, 2008) and may be summarized as "essential in use" and "subject to disruption of supply." Virtually all of the dozens of critical minerals studies conducted since the 2008 NRC report have used some variation of this same definition (Hayes and McCullough, 2018).

The White House Office of Science and Technology Policy (OSTP)-led National Science and Technology Council (NSTC) Subcommittee on Critical Minerals (CMS) developed a critical mineral early warning screening methodology in 2016 and updated it in 2017 (NSTC, 2016; McCullough and Nassar, 2017). This methodology served as the starting point for the development of the technical criteria to identify minerals meeting the critical mineral definition provided by the executive order, using widely accepted criteria published in the mineral commodity literature. Using that methodology, and several other sources of data (Fortier et al. 2018b), the USGS applied two principal quantitative criteria to evaluate minerals for inclusion on the draft list of critical minerals:

- The Herfindahl-Hirschman index (HHI), which measures country concentration of production (DOJ, 2018).
- The USGS net import reliance (NIR) metric based on the USGS annual Mineral Commodities Summaries, published by the National Minerals Information Center (NMIC) of the USGS (USGS, 2018).

With the exception of uranium, all of the data used to calculate both the Herfindahl-Hirshman Index and net import reliance values used to evaluate minerals for inclusion on the critical minerals list are from data compiled by the USGS. The majority of the minerals identified as critical have either an HHI value of >2,500 on a scale from 0 to 10,000 (typically indicating that one or two countries have more than 50 percent of global production or a NIR value of >50 percent (meaning that the United States relies on imports for more than 50 percent of domestic consumption), or both. Data used in both calculations were from calendar years 2017 and 2018.

Federal interagency feedback to the Department of the Interior on the initial draft list highlighted one mineral, uranium, with both fuel and nonfuel uses. Nonfuel uses include armor plating, armor piercing projectiles and radiation shielding (Forsberg and Zucchetti, 2011).The USGS does not track production or above-ground life cycle statistics for uranium, but the U.S. Energy Information Administration (EIA, 2018) data indicated high production concentration and high import reliance. Based on those data, the USGS agreed that it would be consistent with the methodology to include uranium on the critical minerals list.

The critical minerals list, as published in final form by the Office of the Secretary of the Interior, in the *Federal Register* in May 2018 (Table 1), includes 35 critical minerals or mineral groups (e.g. rare earth elements, platinum group

Table 1

Summary of available USGS data and assessments for the 2018 list of critical minerals (*Federal Register*, 2018).

Critical mineral commodity	Sectors						Top producer globally	Top U.S. supplier	Notable example application
	Aerospace (non defense)	Defense	Energy	Telecommunications & electronics	Transportation (non aerospace)	Other			
Aluminum	X	X	X	X	X	X	China	Canada	Aircraft, power transmission lines, lightweight alloys
Antimony		X	X	X	X	X	China	China	Lead-acid batteries
Arsenic		X	X	X		X	China	China	Microwave communications (gallium arsenide)
Barite			X	X			China	China	Oil and gas drilling fluid
Beryllium	X	X	X	X		X	United States	Kazakhstan	Satellite communications, beryllium metal for aerospace
Bismuth		X	X	X		X	China	China	Pharmaceuticals, lead-free solders
Cesium and rubidium	X	X	X	X		X	Canada	Canada	Medical applications, global positioning satellites, right-vision devices
Chromium	X	X	X	X	X	X	South Africa	South Africa	Jet engines (superalloys), rechargeable batteries
Cobalt	X	X	X	X	X	X	Congo (Kinshasa)	Norway	Jet engines (superalloys), stainless steel
Fluorspar			X	X		X	China	Mexico	Aluminum and steel production, uranium processing
Gallium	X	X	X	X		X	China	China	Radar, light-emitting diodes (LEDs), cellular phones
Germanium	X	X	X	X		X	China	China	Infrared devices, fiber optics
Graphite (natural)	X	X	X	X	X	X	China	China	Rechargeable batteries, body armor
Helium				X		X	United States	Qatar	Cryogenic [magnetic resonance imaging (MRI)]
Indium	X	X	X	X		X	China	China	Flat-panel displays (indium-tin-oxide), specialty alloys
Lithium	X	X	X	X	X	X	Australia	Chile	Rechargeable batteries, aluminum-lithium alloys for aerospace

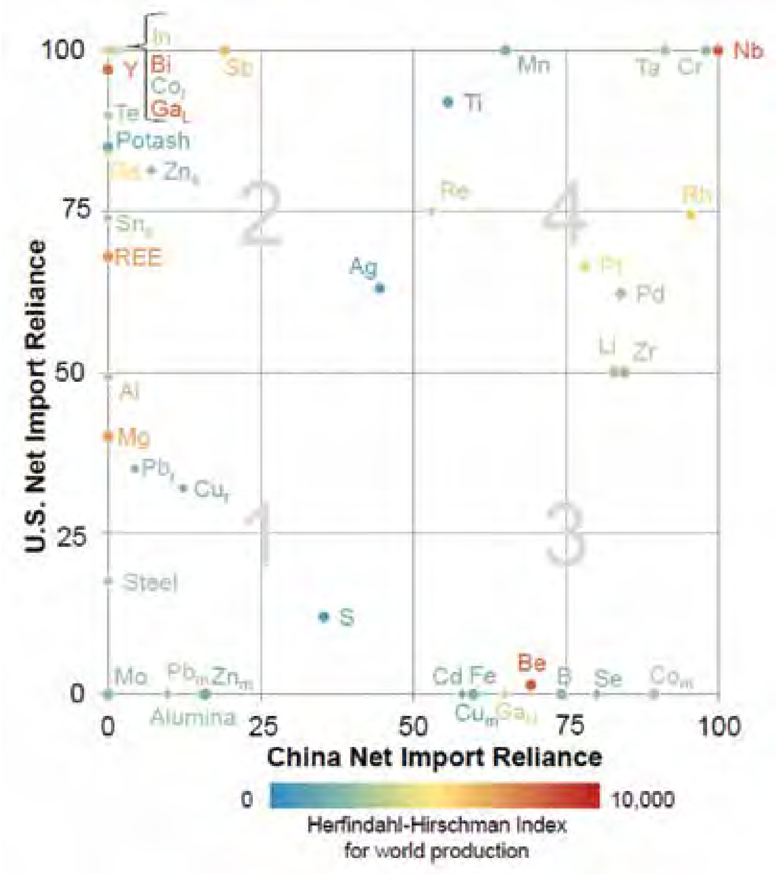
metals). Mineral criticality is not static but rather evolves over time as technology advances and as global supply and demand patterns change. It is anticipated that the critical minerals list will need to be reviewed periodically and updated as appropriate, by the National Science and Technology Subcommittee on Critical Minerals.

The USGS studies aspects of the geologic occurrences of and collects data on the uses, production and consumption of all of the minerals on the critical minerals list. The USGS also studies other minerals not on the

Critical mineral commodity	**Sectors**						**Top producer globally**	**Top U.S. supplier**	**Notable example application**
	Aerospace (non defense)	**Defense**	**Energy**	**Telecommunications & electronics**	**Transportation (non aerospace)**	**Other**			
Lithium	X	X	X	X	X	X	Australia	Chile	Rechargeable batteries, aluminum-lithium alloys for aerospace
Magnesium	X	X	X	X	X	X	China	Israel	Incendiary countermeasures for aerospace
Manganese	X	X	X	X	X	X	China	South Africa	Aluminum and steel production, lightweight alloys
Niobium	X	X	X	X		X	Brazil	Brazil	High-strength steel for defense and infrastructure
Platinum group metals	X		X	X	X	X	South Africa	South Africa	Catalysts, superalloys for jet engines
Potash			X	X		X	Canada	Canada	Agricultural fertilizer
Rare earth elements	X	X	X	X	X	X	China	China	Aerospace guidance, lasers, fiber optics
Rhenium	X		X	X		X	Chile	Chile	Jet engines (superalloys), catalysts
Scandium	X	X	X	X		X	China	China	Lightweight alloys, fuel cells
Strontium	X	X	X	X	X	X	Spain	Mexico	Aluminum alloys, permanent magnets, flares
Tantalum	X	X	X	X		X	Rwanda	China	Capacitors in cellular phones, jet engines (superalloys)
Tellurium		X	X	X		X	China	Canada	Infrared devices (night-vision), solar cells
Tin		X		X		X	China	Peru	Solder, flat-panel displays (indium-tin-oxide)
Titanium	X	X	X	X		X	China	South Africa	Jet engines (superalloys) and airframes (titanium alloys), armor
Tungsten	X	X	X	X		X	China	China	Cutting and drilling tools, catalysts, jet engines (superalloys)
Uranium	X	X	X			X	Kazakhstan	Canada	Nuclear applications, medical applications
Vanadium	X	X	X	X		X	China	South Africa	Jet engines (superalloys) and airframes (titanium alloys), high-strength steel
Zirconium and hafnium	X	X	X	X		X	Australia	China	Thermal barrier coating in jet engines, nuclear applications

Figure 1

Net import reliance of the U.S. (vertical axis) and China (horizontal axis) as a percentage of domestic consumption for 42 minerals for the year 2014. Data denoted by element abbreviation. Circles indicate mine production. Rhombuses indicate refinery or smelter production. Subscripts differentiate between multiple production stages (m=mine production, r=refinery production, s=smelter production, H=high-purity production, L=low-purity production). Each point is colored according to the concentration of that mineral's world production as measured by the Herfindahl-Hirschman Index (HHI) at the country level (From Gulley et al. 2018).



critical minerals list such as gold, copper, zinc, molybdenum, silver and industrial minerals such as sand, gravel, aggregates and phosphate due to their societal and economic importance to the United States. Another important reason why the USGS studies these other minerals is that 12 of the 35 minerals on the critical minerals list are only produced as byproducts from production of other minerals such as copper or zinc that are the primary economic driver for the mine — for example, rhenium is only produced as a byproduct from the mining, smelting and refining of certain types of primary copper-molybdenum ores. Byproduct minerals are discussed further in this article.

U.S. net import reliance for critical mineral raw materials

The United States' reliance on imports of mineral commodities required to support national economic and security interests has been increasing for several decades (Fortier et al, 2015). The USGS collects and publishes information on more than 90 minerals or mineral materials in the annual "USGS Mineral Commodity Summaries (USGS 2018, 2019)." The most recent data indicate that the United States is more than 50 percent net import reliant for 48 mineral commodities and that for 18 of these the net import reliance is 100 percent (USGS, 2019). Critical minerals comprised 14 of the 18 mineral commodities with 100 percent net import reliance and 15 of the 30 remaining commodities with >50 percent NIR.

It is clear from the entries in Table 1 that China dominates global production, and is often the largest supplier to the United States for many of the minerals on the list (gallium, germanium and rare earth elements, for example). On the other hand, even though China dominates global production of fluorspar, the source mineral for the production of hydrofluoric acid, a major industrial chemical with many important uses in industrial processes, the United States sources most of its supply from Mexico. For any given mineral commodity, a high percentage of import reliance does not necessarily mean that the supply is strategically vulnerable. The mineral potash, for example, is the source material for potassium used in mineral fertilizers. Potassium is an essential nutrient for agriculture and has no substitute. Because the United States is highly import-reliant for potash and global production is highly concentrated, potash was included on the critical mineral list. However, as indicated in Table 1, Canada is the world's largest producer and the largest source of U.S. imports. This makes the strategic vulnerability relatively low. The opposite end of the spectrum would be a mineral material such as gallium, which has important uses in nearly every sector identified in Table 1. The United States is 100 percent import reliant for gallium, and China is both the world's largest producer of gallium and the largest source of U.S. imports. The strategic vulnerability for this material would, thus, be considered relatively high. The potential for trade with reliable partners to reduce potential strategic vulnerabilities resulting from high import-reliance has been demonstrated for several minerals, albeit ones that are not all on the critical minerals list (Brainard et al. 2018).

Not all of the minerals on the list have a high U.S. import-reliance. Beryllium and helium, for example, are minerals (broadly defined) for which the United States is a net exporter. Beryllium is the only mineral for which the U.S. Department of Defense has exercised Title III purchasing authority under the Defense Production Act, despite the fact that the United States is the dominant global producer. The concentration of production of ores, concentrates and metal/alloys within single mining and processing operations is the underlying factor that determines criticality in this case. In the case of helium, the Helium Stewardship Act of 2013 mandates the exit of the U.S. government as a supplier no later than 2021, increasing the potential for market disruption during the transition to reliance on the private sector alone as a source. This known, impending change highlights the fact that each of these minerals or mineral materials is in some way unique in terms of mining, processing, use and material form and, therefore, the mitigation strategy for addressing strategic vulnerabilities will need to be customized for each material supply chain.

The United States and China have the two largest economies in the world with substantial requirements for mineral raw material to serve the national interests of each nation. China has become the largest producer and consumer of many of the materials on the critical minerals list during a period of rapid growth in its economy over the past 20 years. China is also increasingly net import reliant for mineral raw materials despite its status as the world's largest producer for many minerals. In a recent USGS comparison of U.S. and Chinese reliance on imports for materials for advanced technology applications (Gulley et al, 2018), critical minerals fall into one of several categories, represented by different quadrants on a plot of United States versus China net import reliance (Fig. 1) and discussed further in this article.

Quadrant 1. Net import-reliance for these minerals is <50 percent for both the United States and China, which indicates that both countries are largely meeting their domestic consumption from domestic production. A metal such as molybdenum, in the lower left corner of quadrant 1, would present no real strategic vulnerability for either country. Not too surprisingly, molybdenum does not appear on the critical minerals list.

Quadrant 2. Net import reliance for these minerals or metals is >50 percent for the United States but <50 percent for China. In addition, several of these are highly concentrated in their production, as indicated by the HHI heat map, and several, including antimony, bismuth, gallium (low purity), germanium, rare earths and yttrium are dominated by production in China. Nearly all the minerals in this quadrant are on the U.S. critical minerals list.

Quadrant 3. Net import reliance for these minerals is <50 percent for the United States and >50 percent for China. Beryllium, for which the U.S. is the world's largest producer, is in this quadrant and, therefore, likely a source of concern for China. Cobalt ore is a clear area of weakness for China and likely explains that country's foreign direct investment strategy in the Democratic Republic of the Congo. It should be noted here that the fact that net import-reliance for the United States for cobalt ore is shown as zero is actually an indication that there is no domestic smelting or refining capacity for cobalt (hence no cobalt ore is imported). Refined cobalt net import reliance for the United States is at the top of quadrant 2. This highlights the fact that strategic vulnerabilities resulting from net import reliance are best understood as a supply chain issue rather than simply a mining or processing capacity problem.

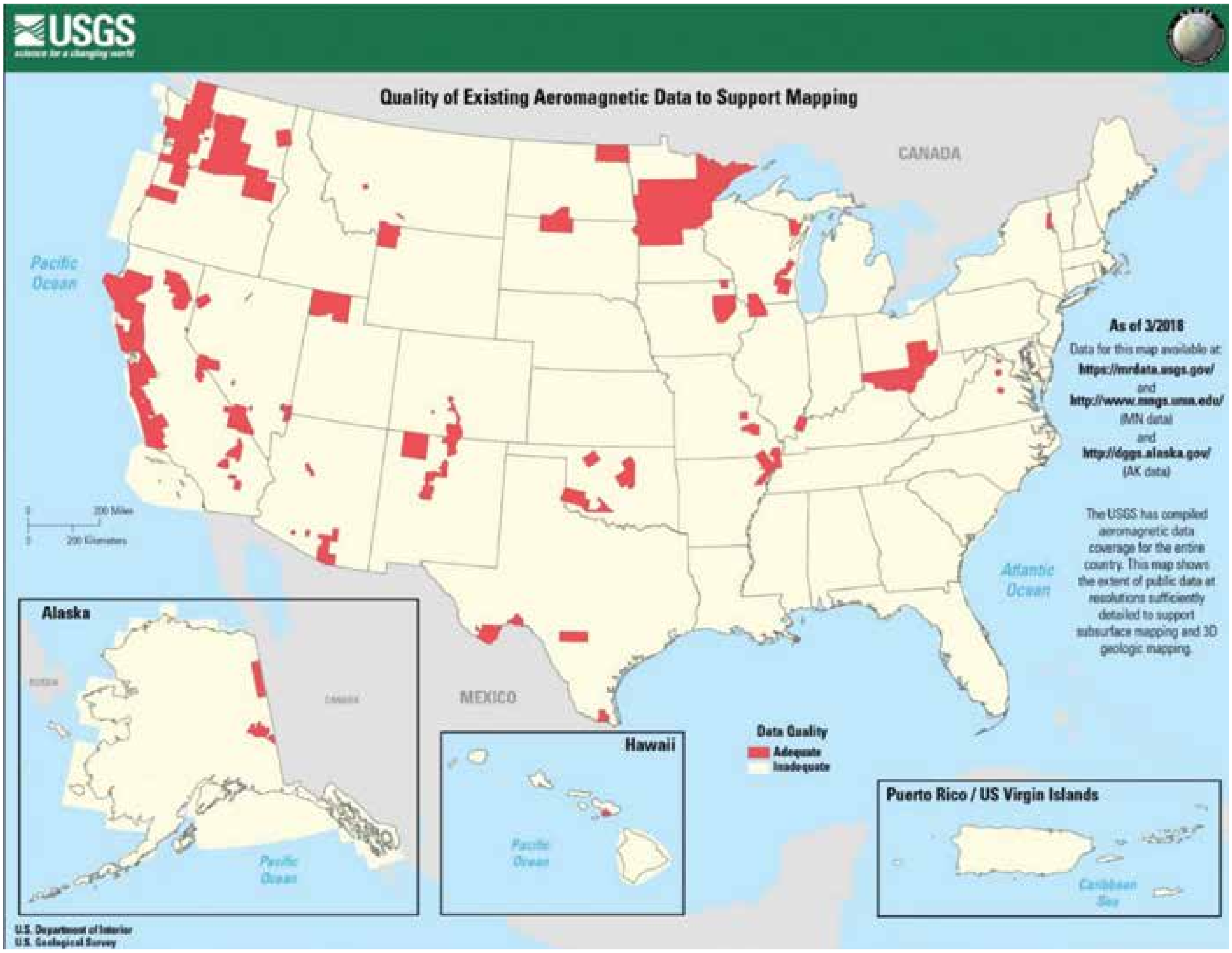
Quadrant 4. Net import-reliance for these minerals is >50 percent for both the United States and China suggesting that these materials are ones for which competition between the world's two largest economies might be expected (Gulley et al. 2018). China's foreign direct investment strategies in Africa for tantalum and chromium, South America for niobium and lithium and Australia for lithium can be interpreted through this filter. All of the minerals in this quadrant are on the U.S. critical minerals list.

Current status of domestic critical mineral resource assessments

Methods are well-established for qualitative and quantitative assessment of the potential occurrences of undiscovered mineral resources for many commodities, and USGS scientists have developed some of the most widely accepted methodological approaches used throughout the world (Singer and Menzie, 2010). As input to these methods, the USGS has developed descriptive and grade-tonnage models for important mineral deposit types from which many metallic minerals are produced domestically in large quantities (including copper, zinc, molybdenum, gold and silver). The descriptive models summarize key geological features most commonly shared by different deposits of a given type, such as geologic environment of formation and geological characteristics (e.g. major and trace elements, mineralogy). By analyzing the geologic settings present within an area of interest such as a country, and the deposit types known to occur in those geologic settings, it is possible to develop a geology-based mineral resource assessment

Figure 2

Quality of existing aeromagnetic mapping for the United States. The entire country has some level of aeromagnetic coverage; however, most of the surveys have vintage data of poor quality or were not designed for use in determining mineral resource potential. For other key airborne geophysical data types (e.g., radiometrics, electromagnetics, gravity, hyperspectral) that are also key to helping understand the nation's critical mineral endowment, ground water resources, geologic hazards and other pressing needs, the spatial coverage of data sets with adequate resolution is even more limited.



As of 3/2018
Data for this map available at:
https://mrdata.usgs.gov/
and
http://www.mngs.umn.edu/
(MN data)
and
http://dggs.alaska.gov/
(AK data)

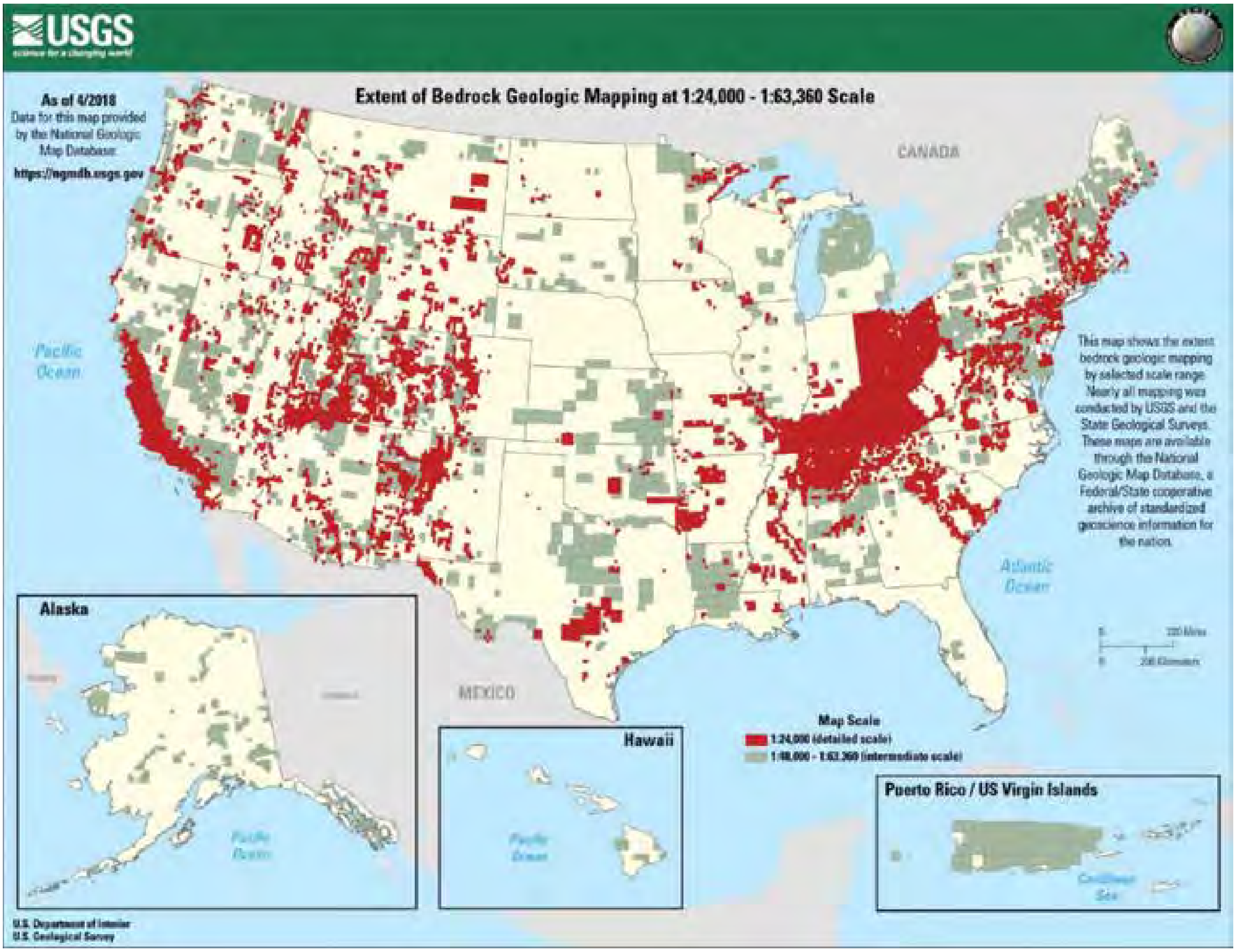
The USGS has compiled aeromagnetic data coverage for the entire country. This map shows the extent of public data at resolutions sufficiently detailed to support subsurface mapping and 3D geologic mapping.

of an area of interest — the mineral resource assessment assesses the likelihood that mineral deposits of given type, ore grade and amount of ore are to occur across the area of interest. The USGS has completed national and global resource assessments for many of these metallic minerals (USGS, 2002, 2000), which contribute to understanding the nation's domestic supply and production in a global context, as well as the short- and long-term global markets and trade options for each commodity.

The USGS has developed these datasets and models and completed resource assessments for a subset of the minerals with low-volume but highly specialized uses (including some on the 2018 list of minerals deemed critical under Executive Order 13817). In 2017, USGS Professional Paper 1802 summarized the current state of knowledge for more than 20 mineral commodities, many of which appear on the critical minerals list (Schulz et al 2017). Professional Paper 1802 contains an inventory of known U.S. occurrences of these critical mineral commodities, but concludes that further studies are needed to determine whether these and additional geographic areas without known occurrences represent future potential sources of domestic supply. A recent USGS evaluation of 4 million ha (10 million acres) of federal lands in parts of Idaho, Montana, Nevada, Oregon and Utah that was done for the U.S. Bureau of Land Management identified areas having moderate or high potential for a variety of critical mineral commodities, including antimony, barite, lithium, tungsten and uranium (Day et al 2016). Studies of domestic beryllium (Foley and Ayuso, 2017; Lederer et al. 2016) and uranium

Figure 3

Current extent of geologic mapping in the United States at both detailed (1:24,000) and intermediate (from 1:48,000 to 1:63,360) scales that are useful for mineral exploration. The map includes some areas for which the geologic mapping, although of sufficiently detailed scale, was completed prior to the mid-1900s; the quality of the mapping in these areas will need to be evaluated as part of prioritizing new investments in mapping.



Extent of Bedrock Geologic Mapping at 1:24,000 - 1:63,360 Scale

As of 4/2018
Data for this map provided by the National Geologic Map Database
https://ngmdb.usgs.gov

This map shows the extent bedrock geologic mapping by selected scale range. Nearly all mapping was conducted by USGS and the State Geological Surveys. These maps are available through the National Geologic Map Database, a Federal/State cooperative archive of standardized geoscience information for the nation.

resources (Hall et al. 2017; USGS, 2015) are underway. In addition, quantitative assessments of platinum-group elements associated with the Stillwater Complex in Montana and the U.S. midcontinent region are ongoing in 2019. These efforts have inventoried available information, identified additional federal and state data sources, and helped refine the understanding of regional needs for detailed geophysical and geochemical data, new geologic mapping, new or updated deposit models and modern mineral resource assessments. As new data are incorporated into updated descriptive deposit models, the USGS's ability to quantitatively assess the potential for undiscovered critical mineral resources improves.

Despite this progress, a number of critical minerals are relatively unstudied, because their importance to the economy has emerged only relatively recently compared to other metallic minerals' long histories of industrial use. As noted previously, 12 of the 35 critical minerals are produced primarily as byproducts of other minerals. For each of the 35 minerals deemed critical under Executive Order 13817, Table 2 provides a summary of whether the United States had domestic production in 2017, and whether the USGS is conducting ongoing research or has conducted resource assessments.

Current status of topographic/geologic mapping and geophysical survey coverage of the United States needed to assess for critical mineral potential

Assessing mineral resources requires a strong foundation of geophysical, geologic and topographic data and maps. Analyses and interpretations of these and other datasets are central to our understanding of the nation's geological endowment of critical minerals. For critical minerals, these data and interpretations also contribute to improved descriptive models of specific mineral deposit types, a better understanding of how mineral deposits form, more refined estimates of the volume and concentration of mineral ores in a given geographic area, a more sophisticated understanding of the rock types that host specific mineral deposit types, more robust mineral resource assessments, and, potentially, additional mineral exploration by the private sector. Such mapping of the nation's subsurface geology will directly benefit our understanding of other economically valuable mineral resources (such as copper, zinc, gold and industrial minerals), energy resources, ground water resources, geologic hazards, geotechnical aspects of infrastructure development and other pressing societal needs.

The USGS has recently conducted a

Table 2

Summary of available USGS data and assessments for the 2018 list of critical minerals (Federal Register, 2018).

Critical mineral commodity	U.S. production in 2017	U.S. reserves	U.S. resources	Ongoing USGS studies	Considered in published USGS regional assessments	Primary commodity	Byproduct/coproduct commodity
Aluminum (bauxite)	no	no	no	no	yes	yes	no
Antimony	no	yes	yes	no	yes	yes	no
Arsenic	No	yes	yes	no	no	no	From copper, gold, and lead smelter flue dust, as well as from roasting of arsenopyrite ores.
Barite	yes	NA	yes	no	yes	yes	no
Beryllium	yes	yes	yes	yes	yes	yes	no
Bismuth	no	NA	NA	no	no	no	Byproduct of processing lead, tungsten, or other metal ores.
Cesium	no	no	no	no	?	no	Byproduct of lithium production.
Chromium	no	yes	yes	no	yes	yes	no
Cobalt	yes	yes	yes	no	yes	yes	yes
Fluorspar	no	yes	yes	no	yes	yes	no
Gallium	no	no	yes	yes	no	no	Byproduct of processing bauxite and zinc ores.
Germanium	yes	NA	yes	yes	no	no	Byproduct of processing zinc or, lead-zinc ores, and coal.
Graphite	no	yes	yes	no	yes	yes	no
Hafnium	no	yes	yes	no	no	no	Byproduct of processing zircon and baddeleyite minerals, mostly from heavy-mineral sands.
Helium	yes	yes	yes	no	yes	no	Natural gas
Indium	no	NA	NA	yes	no	no	Byproduct of zinc and tin processing.
Lithium	yes	yes	yes	no	yes	yes	no
Magnesium	yes	yes	yes	no	?	yes	no
Manganese	no	no	yes	no	yes	yes	no
Niobium	no	no	yes	no	no	yes	no
Platinum group elements	yes	yes	yes	no	yes	yes	no
Potash	yes	yes	yes	no	yes	yes	no

nationwide inventory of the availability of aeromagnetic and other geophysical surveys and geologic mapping, and is identifying needs and priorities for modernizing and regionalizing these datasets to better inform mineral resources assessments and other scientific and societal needs. Nation-wide datasets are far from complete for the high-resolution 3-dimensional geologic maps, geophysical data and digital topographic data needed to understand the distribution of mineral deposits and many other geological features of economic and societal importance. For example:

- The USGS has worked to ensure that the United States is well covered by aeromagnetic and other geophysical surveys, which provide a big picture of the distribution of subsurface rock

Critical mineral commodity	U.S. production in 2017	U.S. reserves	U.S. resources	Ongoing USGS studies	Considered in published USGS regional assessments	Primary commodity	Byproduct/ coproduct commodity
Rare earth elements	no	yes	yes	yes	yes	yes	no
Rhenium	yes	yes	yes	no	no	no	Byproduct of some copper-molybdenum ores.
Rubidium	no	no	no	no	no	no	Byproduct of cesium, lithium and strontium processing.
Scandium	no	no	yes	no	no	no	Byproduct from processing of various ores, tailings, or residues, including from titanium and rare earths (China), uranium (Kazakhstan, Ukraine) and apatite (Russia).
Strontium	no	no	no	no	no	yes	no
Tantalum	no	no	yes	no	no	yes	no
Tellurium	yes	yes	yes	yes	no	yes	Byproduct of processing some copper ores.
Tin	no	no	yes	no	yes	yes	no
Titanium	yes	yes	yes	yes	yes	yes	no
Tungsten	no	NA	yes	yes	yes	yes	no
Uranium	yes	yes	yes	yes	yes	yes	no
Vanadium	no	yes	yes	no	yes	no	Byproduct of processing of uranium, other minerals
Zirconium	yes	yes	yes	yes	yes	no	Coproduct of processing titanium and zirconium mineral concentrates, from mining heavy-mineral-sand deposits.

NA: not available

[a] “U.S. Production in 2017” indicates whether primary (mined) production was reported for 2017. “U.S. Reserves” indicates whether domestic reserves were reported in 2017. Reserves are a subset of resources which could be economically extracted or produced at the time of determination. “U.S. Resources” indicates whether domestic resources were reported in 2017. A resource is a concentration of a mineral or mineral material in a form and amount for which economic extraction of a commodity from the concentration is potentially feasible. Source: USGS Mineral Commodity Summaries 2018.

[b] “Ongoing USGS Studies” indicates whether the mineral is being studied by the USGS.

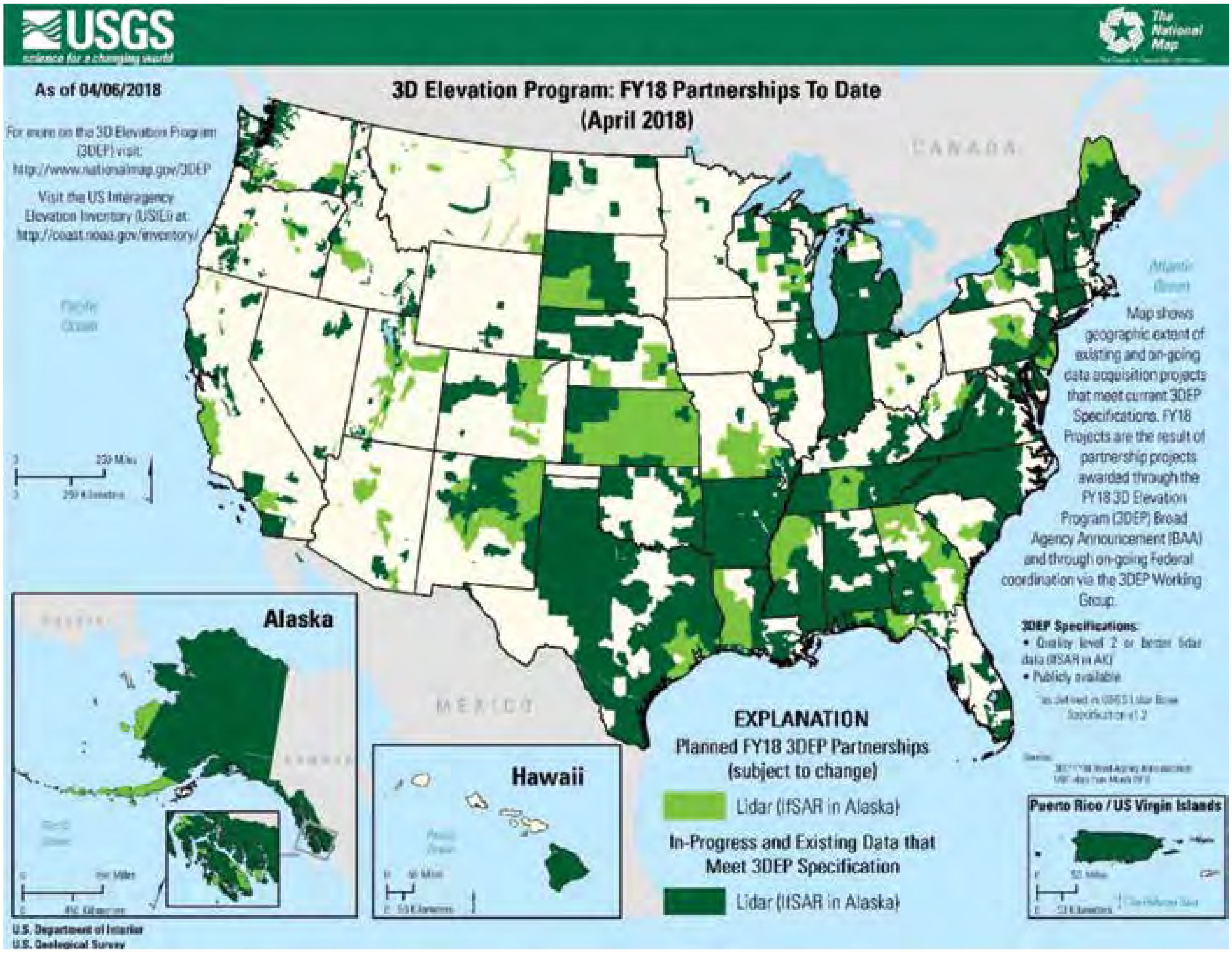
[c] “Covered in Regional Assessments” indicates whether the mineral is covered by selected USGS local- and regional-scale mineral resource assessments. A “?” indicates that a commodity may be mentioned incidentally in some studies such as the occurrence of cesium in the mineral pollucite in certain types of pegmatites.

[d] “Primary Commodity” indicates the commodity that is the primary economic driver for developing a mine.

[e] “Byproduct/Coproduct Commodity” indicates that a byproduct commodity may be recovered during mining for a primary commodity, but is not an economic driver. A coproduct commodity is one that occurs with the primary commodity and may be economically important to recover.

Figure 4

Current extent of topographic mapping in the United States at the resolution of the 3D Elevation Program. Areas shaded green have sufficiently detailed topographic mapping to support geologic mapping of potential mineral resources (approximately 37 percent of United States is mapped at necessary resolution).



types, and can be used to prioritize regions for more detailed geophysical surveys to characterize potential critical mineral resources. However, due to a lack of funding to support nationwide collection of detailed data, less than five percent of the nation has these regional aeromagnetic datasets at the resolution most beneficial to inform mineral resource assessments and private sector exploration (Fig. 2).

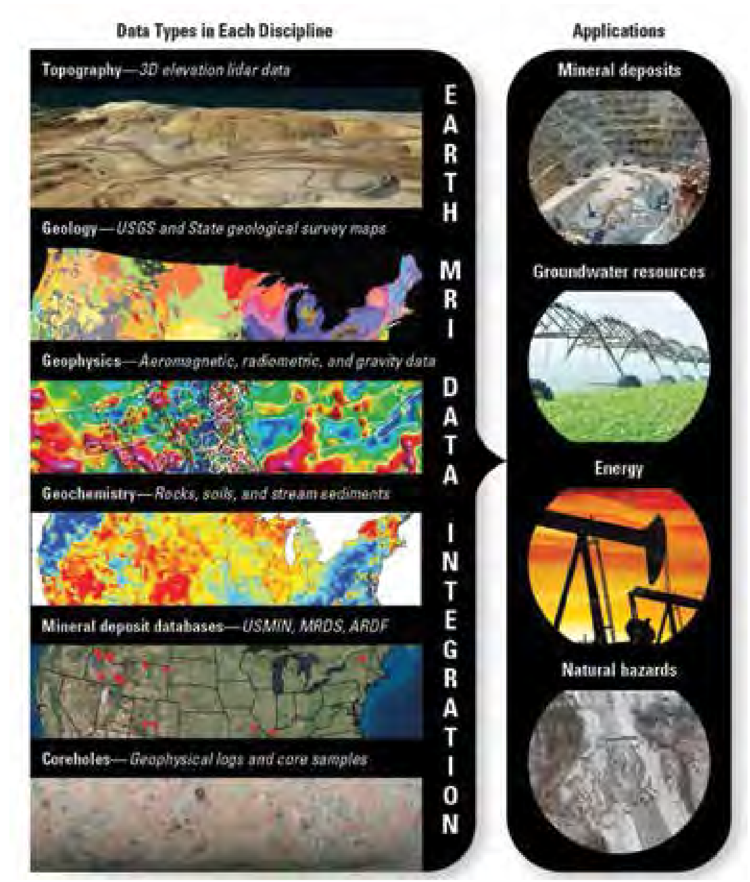
- Through the efforts of the USGS and its state and academic partners, the United States is reasonably well covered by geologic maps at a level of detail useful for regional planning and providing a broad understanding of the distribution of geologic terrains with mineral or energy resource potential. However, less than 18 percent of the nation has been geologically mapped at a detailed scale (1:24,000, i.e., 1 in. = 2,000 ft), and only 31 percent of the United States is covered at intermediate mapping scales (for example, 1:63,360, i.e., 1 in. = 1 mile), which are the map scales typically most useful for assessments of critical mineral potential, geological hazards, ground water and other pressing needs (Fig. 3).
- The USGS estimates that as of the end of 2018, about 53 percent of the nation was covered by topographic data at an appropriate resolution for geologic mapping (Fig. 4).

The Earth Mapping Resources Initiative (Earth MRI)

Undiscovered deposits of at least some of the minerals on the critical minerals list almost certainly exist in the United States, but mineral

Figure 5

Planned applications for data acquired during the Earth Mapping Resources Initiative (Earth MRI) (Day, 2019). Images are from the U.S. Geological Survey (USGS). Sources for images in left column, from top to bottom: Topography: Lidar image of Bingham Canyon openpit mine, Utah (from USGS); Geology: State Geologic Map Compilation geodatabase (USGS Data Series 1052); Geophysics: aeromagnetic map of part of Colorado (USGS Open-File Report 01–0364); Geochemistry: soil geochemical landscapes of the conterminous United States (USGS Open-File Report 2014–1082); Mineral deposit databases: rare earth element production and resource sites in the United States (USMIN database); Coreholes: drill core of granite (from USGS). USGS databases: ARDF, Alaska Resource Data File (https://mrdata.usgs.gov/ardf/); MRDS, Mineral Resources Data System (https://mrdata.usgs.gov/mrds/); USMIN, USGS Mineral Deposit Database (https://minerals.usgs.gov/science/mineral-deposit-database/).



exploration by the private sector is hampered by the lack of modern geological, geophysical and topographic data. In contrast, governments of other countries provide such datasets to the private sector. Studies in Australia and Canada, for example, have reported that investments by their federal governments in these basic geologic and geophysical datasets can be expected to lead to investments five times as large by the private sector (ACIL, 2015; Duke, 2010).

Earth MRI is a partnership between the USGS, the Association of American State Geologists (AASG) and other federal, state and private-sector organizations (Day, 2019). The goal of the effort is to improve our knowledge of the geologic framework in the United States and to identify areas that have the potential to contain undiscovered critical mineral resources. Enhancement of our domestic mineral supply will decrease our reliance on foreign sources of minerals that are fundamental to the nation's security and economy. The intent of the Earth MRI initiative is to leverage the USGS's existing relationships with states and the private sector to conduct state-of-the-art geologic mapping and airborne geophysical and topographic (Lidar) surveys. Analyses of these datasets could point to potential undiscovered critical mineral deposits below the surface.

Earth MRI will identify areas with potential for undiscovered critical mineral deposits (and other essential minerals that are not currently considered critical) that could reduce U.S. mineral import dependence, thereby strengthening national security, creating jobs within the private sector and generating additional economic and social benefits (Fig. 5). Earth MRI will not carry out exploration for critical minerals in the United States. Rather, it will provide basic geological, geophysical and topographic data sets that are suitably detailed for use in critical minerals exploration by the private sector. As noted, Earth MRI's mapping of the nation's subsurface geology will directly benefit our understanding of other economically valuable mineral resources (such as copper, zinc, gold and industrial minerals), energy resources, ground water resources, geologic hazards, geotechnical aspects of infrastructure development and other pressing societal needs.

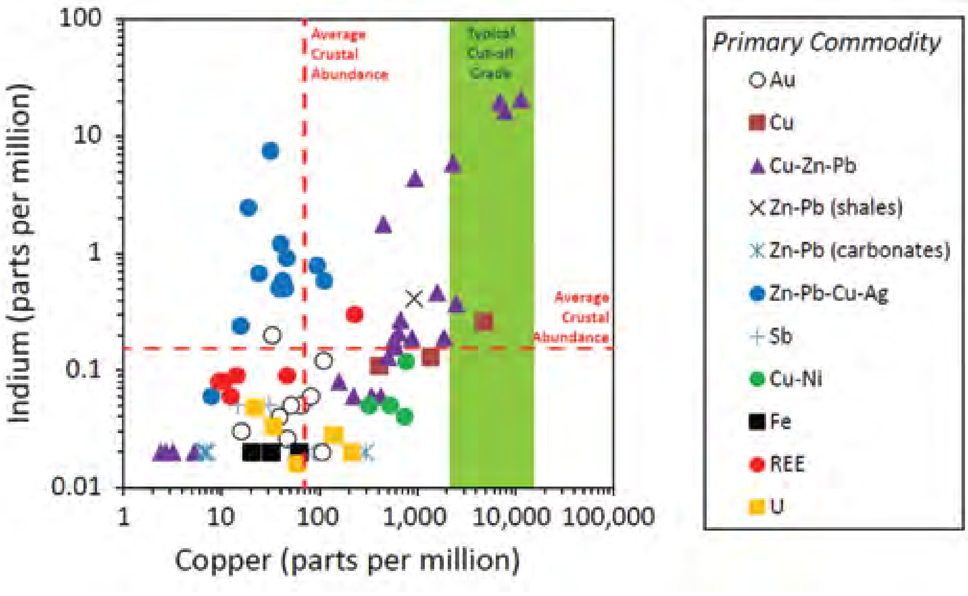
The initial objectives of Earth MRI include new data collection on areas that may contain rare earth elements (Hammarstrom and Dicken, 2019), followed, in the near future, by the development of focus areas for new data collection for other high-priority critical mineral resources to identify new focus areas for integrated studies. The design and implementation of a digital geospatial platform to deliver the new data to the public is also a major objective. This platform will allow the user to access the USGS's authoritative topographic, geologic, geophysical, geochemical and mineral deposit information within a single portal.

Critical mineral potential of waste streams from extractive industries

Solid-waste streams from mineral and some energy extraction represent important potential future sources of critical minerals (Smith et al., 2015). In fact, most critical minerals that are produced as byproducts of the

Figure 6

Plot of indium and copper for mill tailings samples mined for various primary commodities. The average crustal abundance of indium and copper are shown as red dashed lines for comparison. Typical copper cut-off grades for porphyry copper deposits are shown as the green field. Modified from Seal and Piatak (2017).



mining of other commodities are derived from these waste streams of primary commodities. However, byproduct recovery is not currently implemented at all facilities where it could be and recovery efficiencies of byproduct critical minerals vary greatly. The need for many critical mineral commodities can be considered new demand because technological innovations now require these commodities that in the past may have had limited uses. Thus, existing solid wastes from past mining activity may represent important above-ground sources of these commodities with the possible advantage of already having had extraction and initial stages of ore processing done. Reprocessing of existing mine waste may have the added bonus of improving environmental protection at inactive and abandoned mines as materials are being reworked.

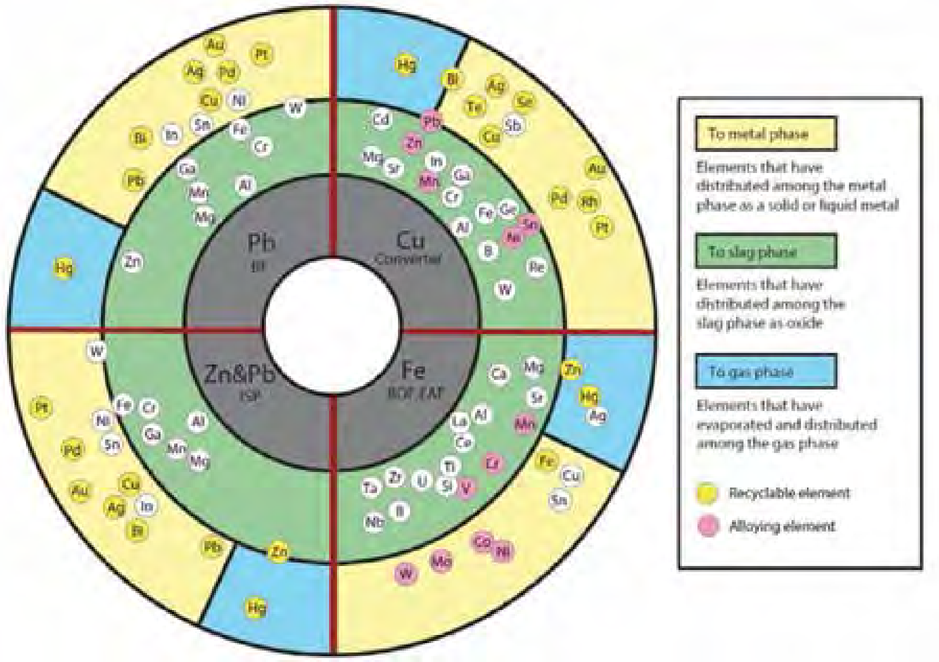
Mining operations, both historically and today, typically produce a single primary commodity or two or three coproduct commodities. Byproduct recovery is not uniform across the extractive industries. Instead, the recovery of byproduct commodities is influenced by a number of factors: the degree to which a byproduct commodity is enriched at various stages of resource processing; the endowment of a specific byproduct commodity in a given deposit; the availability of technology to effectively extract or concentrate that byproduct commodity and the capital needed to build ore-processing circuits at mines, mills, and refineries to recover those byproduct commodities.

Critical minerals can span the spectrum from primary commodities to coproduct and byproduct commodities that vary on the basis of commodity and mineral deposit type. Some critical mineral commodities, such as the rare earth elements, antimony, beryllium and lithium, are commonly produced as primary commodities. Among the primary commodities, highly efficient operations can exceed 90 percent recovery, meaning that 10 percent or less of the commodity ends up in various waste streams related to mining and ore-processing. Other commodities, such as the platinum-group elements (platinum, palladium, iridium, osmium, rhodium and ruthenium), can be produced as either a primary commodity or as a byproduct. The Stillwater Mine in southwestern Montana is an example of a primary producer of platinum-group elements, whereas the Eagle Mine in the Upper Peninsula of Michigan is a byproduct producer.

A third type of critical mineral commodity is produced solely as a byproduct of mining for other commodities. For example, the dominant source of critical mineral commodities tellurium, selenium and rhenium is copper mining, specifically the mining of porphyry copper deposits. Porphyry copper deposits are large-tonnage, low-grade copper deposits commonly found in Arizona, New Mexico, Nevada, Montana, Utah and Alaska (John et al. 2010). Likewise, the dominant source of the critical mineral commodity germanium is zinc mining. Important sources in the United States are the zinc mines in central Tennessee, the Red Dog Mine in Alaska, and the Pend Oreille Mine in Washington (Leach et al., 2010; Emsbo et al., 2016). The behavior of these byproduct commodities follows two general patterns. The first pattern is when the byproduct of interest is incorporated as a substitution in a primary ore mineral. For example, germanium substitutes into the crystal structure of sphalerite, the predominant zinc ore mineral. The processing of sphalerite ores usually results in recovery of more than 90 percent of the germanium excavated during zinc mining at operations that recover germanium. Similarly, rhenium substitutes into the molybdenum

Figure 7

Element "radar" chart showing distributions of elements among metal, slag, and gas phases during various types of pyrometallurgical processing. BOF, basic oxygen furnace, EAF, electric arc furnace, BF, blast furnace, ISP, imperial smelting process. From Piatak (2017).



mineral molybdenite and a recovery of more than 90 percent of the rhenium removed from the ground is typical at operations that process their molybdenite concentrates for rhenium. In contrast, the tellurium usually forms discrete telluride minerals that may occur as inclusions in ore minerals being concentrated during ore processing and in waste minerals that are being discarded during ore processing, such as is the case with porphyry copper mines that are the most common source of tellurium. At active copper mining operations that recover tellurium, less than 5 percent of the tellurium that is mined from the ground is actually recovered. The rest escapes recovery in various waste streams at the mine and ore-processing facilities. Vanadium – essential for jet engines, airframes and high strength steel – is mostly derived from petroleum residues, iron slag (a common waste product from the iron industry), and from uranium mining. Considerable current research is focused on extracting rare earth elements from coal ash – a ubiquitous waste product of coal utilization.

Byproduct critical minerals possess additional complexities when considering economic viability compared to primary commodities. For primary critical mineral commodities, the economic viability can be directly linked to the ore grades and associated mining costs. For these deposits, a cutoff grade defines the concentration of the commodity needed for profitability of a mining operation. Rock with grades above the cutoff grade will be mined, and those rocks below that grade will either be avoided during mining, discarded as waste or stockpiled until economic conditions become more favorable. Because the concentration of byproduct critical minerals does not determine the economic viability of a mine, the cutoff grade for byproduct commodities reflects the limits of technological feasibility to extract and concentrate that element. That concentration will vary on the basis of the specific mine in question and on the specific approach used to extract an element, which means identifying prospective mine wastes from legacy mine sites that are suitable for critical mineral extraction can be challenging. An initial screening approach to identify anomalous concentrations of mineral commodities can use the average crustal abundance of those elements to determine the magnitude of enrichment of these elements (Seal and Piatak, 2017). For example, a suite of mill tailings samples from a variety of mineral deposit types highlights tailings samples from some deposit types that exceed the average crustal abundance of indium by a factor of up to 100. Similar levels of enrichment are also seen in copper concentrations (Fig. 6).

Waste streams span a variety of materials that vary on the basis of the commodity being mined and how ores are processed. For base metal deposits, such as those mined for copper, lead, zinc and nickel, the ores are typically crushed and ground to the size of silt or sand. The minerals are commonly concentrated through froth flotation. The waste material from this process (tailings) is then disposed of in a tailings storage facility. The ore mineral concentrate is then either processed using hydrometallurgical or pyrometallurgical processes to further extract and refine the metal of interest, usually followed by electrochemical refining techniques. Pyrometallurgy produces a metal alloy (which is then refined electrochemically), a solid waste (slag), and gaseous discharges (Piatak, 2017). Critical elements may variably segregate into each of these outputs (Fig. 7). Each step of the process has its own unique solid residue, which may or may not concentrate various critical minerals. For example, for both germanium and tellurium, the residue from the final electrochemical refining step is the material from which these critical elements are recovered.