USGS critical minerals review

Steven M. Fortier, Nedal T. Nassar, Jeffrey L. Mauk, Jane M. Hammarstrom, Warren C. Day and Robert R. Seal
U.S. Geological Survey.

A report titled "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals" was released by the U.S. Department of Commerce on June 4, 2019 (U.S. Department of Commerce, 2019). The report, developed through an interagency process in response to an Executive Order (EO) of the same name (Executive Order 13817, 2017), formalized a whole-of-government strategy for reducing the strategic vulnerabilities associated with high import reliance for critical mineral raw materials that are important for U.S. economic and national security interests. Through six calls to action defining 24 goals, a total of 61 specific steps were described to achieve the objectives of the EO, to be carried out by multiple U.S. government departments and agencies. The National Science and Technology Council (NSTC) Critical Minerals subcommittee was tasked in the report with monitoring the progress of the implementation of the recommendations. Lead departments or agencies have been identified for each of the calls to action defined in the report.

The six calls to action, with the associated agency lead(s), are:

1. Advance transformational research, development, and deployment across critical mineral supply chains (U.S. Department of Energy).
2. Strengthen America's critical mineral supply chains and defense industrial base (U.S. Department of Defense).
3. Enhance international trade and cooperation related to critical minerals (U.S. Department of State and U.S. Department of Commerce).
4. Improve understanding of domestic critical mineral resources (U.S. Department of the Interior).
5. Improve access to domestic critical mineral resources on federal lands and reduce permitting timeframes (U.S. Department of the Interior and U.S. Department of Agriculture).
6. Grow the American critical minerals workforce (U.S. Department of Education and the National Science Foundation).

These calls to action represent several themes that underlie critical mineral issues. The first underlying theme is the importance of innovation and research and development (R&D) as part of the solution to mitigate strategic vulnerabilities relating to mineral imports. The economics and regulatory frameworks of host countries in which the extractive industries operate are major factors that drive import reliance. It is often simply more cost-effective for consumers of mineral raw materials to source them from jurisdictions where there is less concern about the negative externalities associated with mining and mineral processing. In the past, ignoring such externalities has resulted in legacy mine environmental impacts that underlie the negative perceptions of the mining industry by much of the general public in the United States. This is clearly not a sustainable path forward for the domestic mining industry. Instead, reducing reliance on imports can be facilitated by innovation in mining and mineral processing to lower costs and improve industrial competitiveness, while maintaining acceptable environmental standards as well as through R&D into the development of substitutes for critical minerals, improvement in the efficiency of material usage and the development of recycling technologies.

A second underlying theme is that critical mineral issues are inherently supply chain issues. It is not always the case that the strategic vulnerability for a given mineral commodity is a mining and concentrate production issue. The vulnerabilities often lie further down the supply chain. Simply establishing domestic mining and concentrate production does nothing to mitigate risks if downstream processing is highly concentrated geographically, imported and unreliable. An example is the mineral graphite. While graphite production is still highly concentrated globally, supply is diversifying quite rapidly, particularly with large projects coming into production in Africa. The real issue for graphite supply for the rapidly growing market for lithium-ion batteries is the downstream purification of flake graphite and especially the production of the spherical graphite form required for lithium-ion battery anode production. Subsequent iterations of the critical minerals list will identify specific forms and supply chain nodes that are of greatest concern in order to highlight the supply chain risks. It is important to note, in this context, that each of the minerals on the critical minerals list has its own supply chain and is in some way unique in terms of geologic occurrence, ore grade, host mineralogy, extractive metallurgy or other processing requirements, and hence each needs to be evaluated individually to develop commodity-specific mitigation strategies.

A third underlying theme acknowledges the complexity of modern, industrial manufacturing chains, that are often multinational in scope and highlight the observation that import reliance is not equivalent to import vulnerability (Fortier et al., 2015). Imports of mineral raw materials from reliable trade partners, such as Canada, Mexico and Australia, among others, can in fact be a strategic advantage rather than a vulnerability. A recent U.S. Geological Survey (USGS) study demonstrates that net import reliance for several critical minerals is less than 50 percent of domestic consumption, the threshold value used in evaluating minerals for inclusion on the critical minerals list, when viewed from a North American (i.e., including Canada and Mexico) perspective (Brainard et al., 2018). Bilateral and multilateral initiatives for joint efforts to secure critical minerals supply chains are tangible results of the recommendations in the federal critical minerals strategy, which are already being realized (U.S. Department of State, 2019).

A fourth underlying theme, and the subject of much of the rest of this year's critical minerals review, emphasizes the rich domestic endowment of U.S. mineral resources. Despite an abundance of U.S. mineral resources for many of the minerals on the critical minerals list, many deposits remain undeveloped for a variety of reasons. An important component of the federal critical mineral strategy is aimed at a better understanding of domestic resources, identifying and addressing the barriers to producing them and improving access to them.

There are several aspects of this fourth underlying theme being addressed by the Mineral Resources Program (MRP) of the USGS through mineral information and databases, mineral resource assessments, mapping and geophysical surveys, and mineral research functions. These include:

1. Mineral information. The National Minerals Information Center (NMIC) collects, analyzes and publishes information on supply, demand and consumption for more than 90 minerals or mineral materials of importance to the U.S. economy and national security. These data enable the estimation of mineral import reliance, mineral criticality modeling, risk analysis and studies of supply security for mineral raw-material supply chains.
2. Mineral deposit databases. The United States has a long history of mining activities. Data from a variety of public sources are being compiled and released, by commodity, with a focus on critical minerals, by the USMIN project within the MRP.
3. Mineral resource assessments. The USGS has a long history of conducting domestic and international mineral resource assessments and developing methodologies to facilitate qualitative and quantitative assessments.
4. Mapping and geophysical surveys. The Earth Mapping Resources Initiative (Earth MRI) aims to establish a framework to facilitate private-sector mineral exploration as well as supporting other important societal goals in the areas of water resources, hazards mitigation, land management decisions and ecosystem conservation.
5. Mineral research. Ongoing research initiatives include the evaluation of unconventional sources of critical mineral resources such as mill tailings and other mine wastes.

Work in each of these areas is discussed in this article. The objectives of the federal critical mineral strategy provide a useful framework and focus for much of the work being done in the USGS–MRP. While a detailed discussion of all the calls to action in the EO is beyond the scope of this paper, the work of the USGS–MRP provides a foundation for prioritizing the critical minerals list and a basis for the development of mineral-specific mitigation strategies, which are important for the implementation of other parts of the federal strategy.

Mineral information: mineral criticality methodology development

Numerous studies on mineral criticality methodology have been published over the past decade, resulting in a variety of critical mineral lists, each of which differ somewhat in detail (Hayes and McCullough, 2018). An interagency group within the U.S. federal government has an ongoing effort to evaluate evolving mineral criticality using screening methodologies developed over the past several years which rely principally on data collected by the NMIC at USGS (NSTC, 2016; McCullough and Nassar, 2017). Recent work by Nassar et al. (2020) built upon this previous work by enhancing it and using the most up-to-date data available. Specifically, mineral commodities were evaluated using a risk-modeling framework where risk was defined as the confluence of three factors:

hazard, exposure and vulnerability. In the context of mineral commodity supply risk, these three components of the "risk triangle" (Crichton, 1999) translate to:

- The likelihood of a foreign mineral commodity supply disruption (the hazard).
- The dependency of the U.S. manufacturing sector on foreign mineral commodity supplies (the exposure).
- The ability of the U.S. manufacturing sector to withstand a mineral commodity supply disruption (the vulnerability).

Each of these components of supply risk, beginning with the hazard, is discussed below.

Mineral commodity supplies can be disrupted by a variety of factors ranging from trade disputes and conflicts to mine accidents and earthquakes (Hatayama and Tahara, 2018; Schnebele et al., 2019). These factors can be categorized into issues related to a country's (in)ability to supply (e.g., due to labor strikes) and those related to a country's (un)willingness to supply (e.g., due to trade disputes). In their analysis, Nassar et al. (2020) proposed that, all else being equal, the likelihood of a supply disruption is greatest when production is concentrated in countries that may become unable or unwilling to supply. Their assessment of this "hazard" is thus based on an indicator of production concentration — as measured by the Herfindahl-Hirschman Index (HHI; Herfindahl, 1950) — weighted by each country's ability and willingness to supply to the United States, where ability is based on the Fraser Institute's Policy Perception Index (Stedman and Green, 2018) and willingness is based on a newly derived index comprising a country's trade ties, shared ideological values, and military cooperation with the United States.

Exposure to a foreign mineral commodity supply disruption is largely dependent on the degree to which the United States imports materials from other countries for consumption by its domestic industries. The dependency of the U.S. manufacturing sector on foreign supplies or Trade Exposure (TE) was thus assessed (Nassar et al., 2020) using the same Net Import Reliance (NIR) metric used in the original assessment used to define the critical minerals list (Fortier et al., 2018).

When companies are faced with a mineral commodity supply disruption, they may deal with the situation in different ways based on their circumstances and the commodity in question. They may use substitute materials, absorb or pass through part, or all, of any resultant price increase, or utilize strategic inventories. None of these options is necessarily desirable. Substitution typically results in lower product performance and (or) increased costs; absorbing commodity price increases results in lower profits; passing cost increases to customers erodes demand; and maintaining large inventories increases costs and ties up working capital.

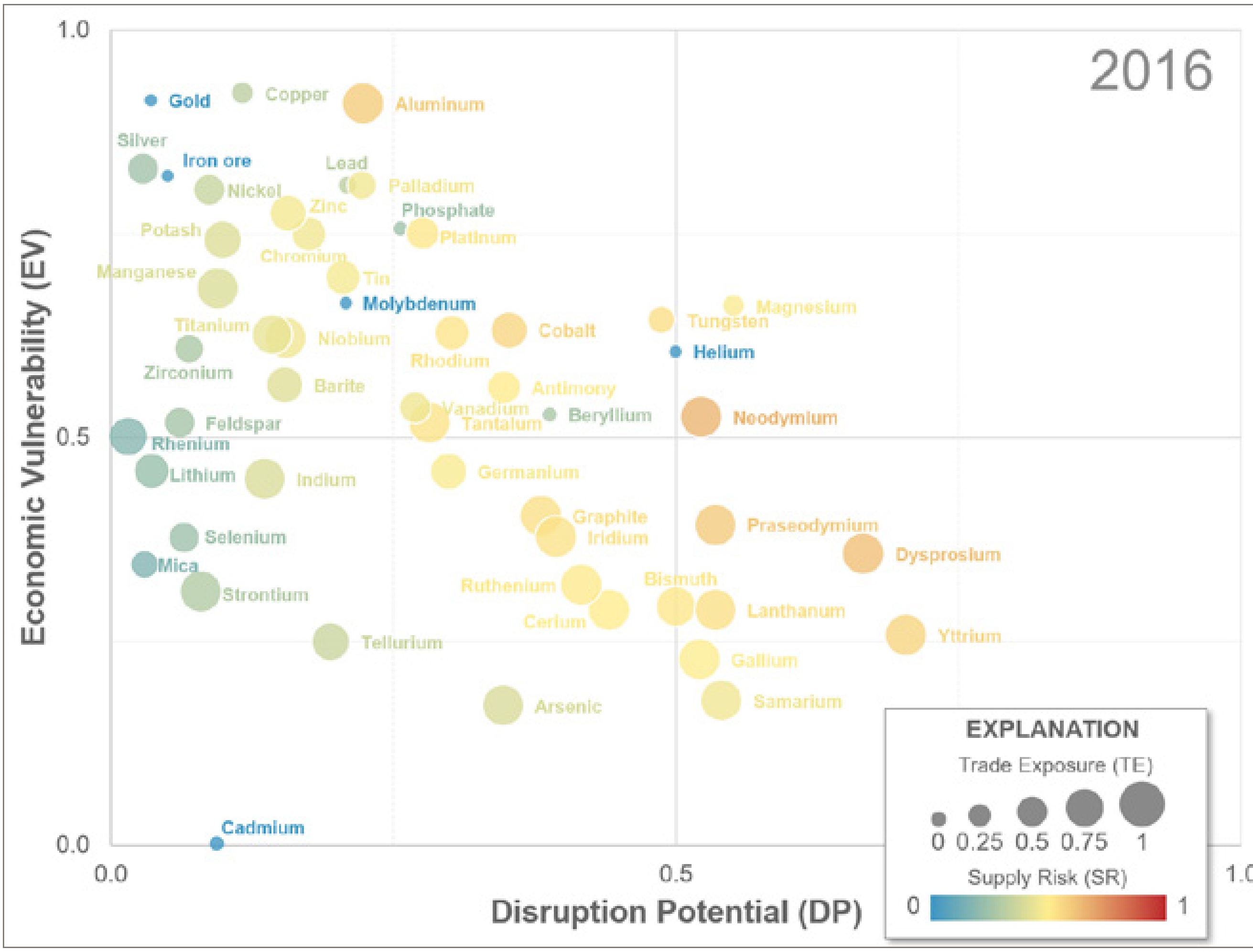
Nassar et al. (2020) proposed that the ability of a company or industry to utilize any of these options diminishes when its profitability is low. All else being equal, companies or industries that have lower profitability are thus more vulnerable to commodity supply shocks than those with greater profitability. Similarly, the larger the expenditures are on a specific commodity, the more vulnerable a company or industry will be to a supply shock of that commodity. Accordingly, a metric was developed to assess economic vulnerability (EV) based on the ratio of expenditure on a specific commodity, by industry, relative to that industry's operating profits. These industry-specific vulnerability ratios were then aggregated across all consuming industries in the manufacturing sector based on each industry's contribution to the U.S. Gross Domestic Product (GDP). To do this, Nassar et al. (2020) linked data on U.S. consumption of individual commodities by application to specific U.S. industries as defined by the North American Industry Classification System (NAICS). Data on each industry's profitability were then obtained from the U.S. Census Bureau (U.S. Census Bureau, 2017, 2019).

These three indicators thus capture the different components of risk: hazard, exposure and vulnerability. Importantly, each of these factors is a necessary, but alone insufficient, component of risk. For example, there may be a high likelihood of a foreign supply disruption for a certain commodity, but if the United States is not import-reliant or if the U.S. manufacturing sector does not consume significant quantities of that commodity, then the overall risk is low. Similarly, if the United States is highly import-reliant, but there are many highly reliable sources of supply, then the overall risk is again low.

Results for the year 2016 (the most recent year for which complete data were available) are displayed in a scatter plot format in Fig. 1, with disruption potential (DP, the hazard) depicted on the horizontal axis, economic vulnerability (EV, the vulnerability) depicted on the vertical axis, trade exposure (TE, the exposure) depicted as the point size, and the overall supply risk (SR)

Figure 1

Assessment of mineral commodity supply risk to U.S. manufacturing sector for year 2016. From Nassar et al., 2020.



depicted as the point shade (Nassar et al., 2020).

Mineral commodities that are positioned in the lower left of Fig. 1, including cadmium, strontium, mica and selenium, have relatively low DP and EV. Conversely, mineral commodities in the upper left including copper, silver and nickel have relatively low DP but high EV. Mineral commodities for which the United States was a net exporter, including gold, molybdenum and helium, are depicted with the smallest point size indicating low TE and a point shade of blue indicating an overall low SR. Commodities that have the greatest overall SR for 2016 include several rare earth elements, cobalt and aluminum, and they are depicted in the warmest colors (orange to red).

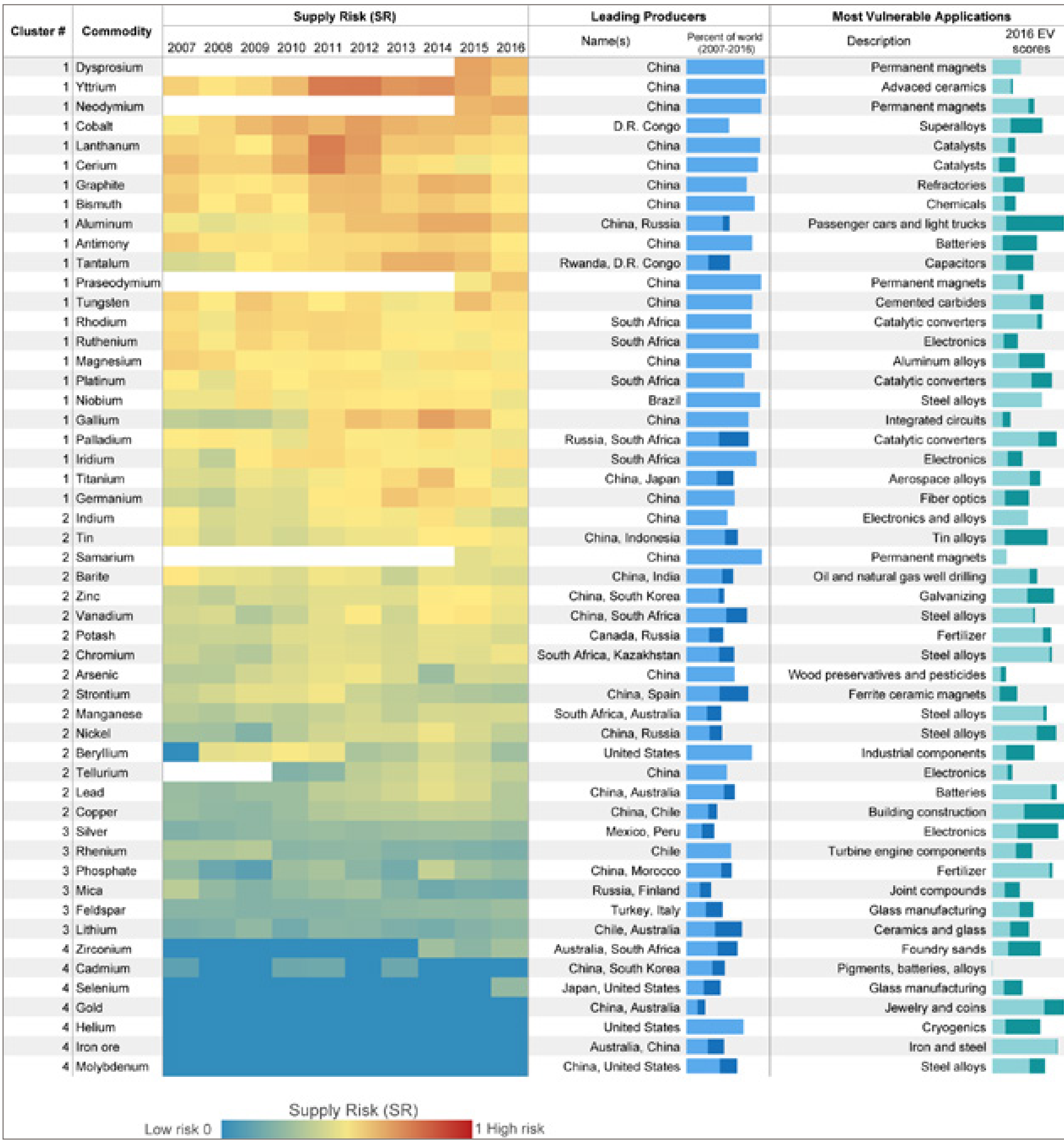
In Fig. 2, the commodities are ranked based on their average SR, from highest to lowest, over this time period and a hierarchal cluster analysis was used to identify the subset of commodities of greatest concern. This subset of commodities (denoted as Cluster #1) includes several rare earth elements, cobalt, graphite, tantalum and the platinum-group metals. Notably, China was a leading producer for 16 of the 23 mineral commodities in this top cluster (if one considers that China was the largest refiner of cobalt, whereas the Democratic Republic of the Congo was the largest miner of cobalt).

The results indicate that, aside from a few commodities (e.g., gallium) that witnessed a notable shift in SR, the SR for most commodities remained relatively consistent, suggesting that dramatic changes in SR over short periods of time are infrequent.

As noted earlier, each factor — hazard, exposure and vulnerability — is a necessary component of risk. In turn, a reduction in any one of these factors reduces risk. The development of domestic primary or secondary (i.e., recycling) production that reduces or eliminates import reliance also reduces the overall supply risk. Similarly, diversification of global supply and the reduction of use decreases

Figure 2

Supply risk heat map for years 2007-2016, leading producers and most vulnerable applications. From Nassar et al., 2020.



the overall supply risk by reducing the likelihood of a supply disruption and the impact that a disruption may have on the consuming industries, respectively.

Approaches highlighted in the federal critical mineral strategy, such as diversifying supply, developing domestic primary and secondary resources, developing substitute materials, maintaining strategic inventories and strengthening trade relations have significant potential, as well as limitations, for reducing the overall supply risk that is unique to each commodity and each industry sector. As noted above, an important task going forward is to determine which strategies are most effective for each commodity-specific supply chain.

Mineral deposit databases: USMIN project

The USGS is developing comprehensive 21st century geospatial databases that are the most authoritative source of important information about mines and mineral deposits in the United

States and its territories. The databases provide high-quality mineral deposit data to support land management actions and policies, deliver electronic mineral deposit databases for the nation and provide electronic data and metadata, at no cost, on the USGS website.

The USMIN project is developing two types of databases: (1) a database that depicts mine-related locations or features that have been shown on USGS topographic maps and (2) databases that provide information on the most important mineral deposits in the United States. This section provides a brief description of the former, and a fuller description of the latter, which contain the information on critical minerals.

The locations of mine sites in the United States have been shown on USGS topographic maps since the origin of those maps in 1884. In 2009, the USGS moved from traditional printed topographic maps to a digital topographic map product based on eight data layers from The National Map (Usery et al., 2009). Mine sites and mining-related features formerly shown on the paper topographic maps were, and continue to be, omitted from the newest generation of digital topographic maps. Because these mine features provide an invaluable landscape-scale record of pre-2009 mining activities in the United States, in 2013 the USMIN project began digitizing prospect- and mine-related features from historic USGS 7.5- and 15-minute topographic quadrangle maps of the United States. In August 2016 the first version of this database was released to the public and was revised in 2017, 2018 and 2019 to include additional completed states (Horton and San Juan, 2019). Work is underway to complete digitizing for the remaining co-terminus states in the central Atlantic and northeastern United States.

USMIN has published databases for seven of the 35 minerals or mineral groups included in the federal critical minerals list: cobalt, lithium, rare earth elements, rhenium, tellurium, tin and tungsten (Burger and Long, 2018; Burger et al., 2018; Carroll et al., 2018; Karl et al., 2018; Bellora et al., 2019; Karl and Mauk, 2019; Karl et al., 2019). Three databases, as of this writing, are in review — germanium, niobium and tantalum — and six are in progress — beryllium, chromium, graphite, indium, platinum-group metals and titanium. These 16 critical minerals include some of the minerals with the highest U.S. import reliance (U.S. Geological Survey, 2020). USGS professional paper 1802 "Critical mineral resources of the United States — economic and environmental geology and prospects for future supply" provides comprehensive information on many of these critical minerals (Schulz et al., 2017).

The USMIN team has set lower limits on the size of the deposits that are included in our critical mineral databases. In some cases, such as tungsten, where there are hundreds or even thousands of former mines that produced a commodity, setting a lower limit is clearly necessary. Where data are adequate, the USMIN team compiles production and resource data and then selects a cutoff that is less than known endowments of deposits that are currently producing on a global basis but still captures deposits in the United States that have large endowments. In the case of tungsten, it used only the deposits in the 90th percentile or greater, which yielded more than 30 deposits (Carroll et al., 2018). As there has been no known production of tungsten in the United States since 2015 (U.S. Geological Survey, 2020), this is one way to identify deposits that are large enough that they might contribute to future production. However, some stakeholders may have a need to identify resources that are much smaller, in part because greenfield or brownfield exploration may transform a deposit with negligible known resources to a producing mine.

In some cases, setting a lower limit on the endowment for mineral deposits is relatively easy. For example, as discussed below, byproduct elements such as germanium and tellurium are produced from deposits whose profitability relies on other elements: lead-zinc deposits may produce byproduct germanium, and copper deposits may produce byproduct tellurium. Because byproduct production may not materially influence a company's bottom line, and because it can be difficult to track and quantify byproduct production, data are often limited. In some cases, a lower limit for a commodity can be set by selecting only deposits that have recorded production or resources of a commodity. This is the case for tellurium, which occurs in many porphyry copper deposits in the western United States, but which is often not recovered from those deposits. However, only one deposit — in Butte, MT — has recorded production figures for tellurium and, to our knowledge, there are no deposits in the United States that list their tellurium resources. Consequently, the USMIN tellurium database contains only one deposit: Butte (Karl and Mauk, 2019).

USMIN only compiles data that are available in the public domain, including published journal articles, reports by state and federal agencies and reports from the minerals industry. Reports by mining companies that are not public, or written communications that are not made public are not used to inform USMIN databases. As with all databases, the quality of a database relies on the quality of the underlying data. In some cases, the data are detailed, and the quality of resource estimations is robust. In other cases, however, resources that have been listed by some companies are based on widely spaced drill holes or untested extraction technologies, or a new deposit type whose potential for the commodity of interest remains unknown or a combination of these. Nonetheless, the USMIN team relies on publicly available information to build databases, and because these are databases, there is no step to screen out any publicly available data.

As discussed below, the USGS is undertaking research to help identify unconventional mineral deposits. For some commodities, such as lithium, the minerals industry is already pursuing unconventional resources. Past production of more than 15 kt (16,535 st) lithium in the United States has come from pegmatite deposits of the Kings Mountain belt in North Carolina and from the Clayton Valley brine deposit in Nevada (Fig. 3A). Sources of U.S. production are comparable to global production, where pegmatites and brines are the predominant sources of lithium (Kesler et al., 2012). In addition to these conventional resources, the United States has unconventional resources that have not produced lithium commercially but may contain large quantities of lithium. For example, oilfield brines of the Smackover Formation in Arkansas have been used as a source of bromine since 1957, and work is underway to test new technology to recover lithium from those oilfield brines after bromine has been recovered (Eccles et al., 2018). Similarly, the Great Salt Lake of Utah has a considerable lithium resource, and extraction of lithium could be coupled with existing extraction of magnesium (Whelan and Petersen, 1976). Furthermore, geothermal fields, such as those in the Salton Sea area of California, may produce lithium in the future from geothermal brines (Gruber et al., 2011). These unconventional brine deposits all have lower grades than the producing Clayton Valley brine operation, as shown in a grade-tonnage plot (Fig. 3B). However, their economic viability is significantly influenced by the presence of existing operations, and recovery of lithium as a byproduct may prove to be economic for some operations. Hydrothermally altered sedimentary rocks can also contain lithium in the clay mineral hectorite ($Na_{0.3}(Mg,Li)_3Si_4O_{10}(F,OH)_2 \cdot nH_2O$), and significant deposits have been identified in the western United States (Bradley et al., 2017; Karl et al., 2019). So far, none of these deposits is in production, but if they are further developed and prove to be economic, their large endowments could make significant contributions to lithium production in the United States.

Mineral resource assessments: recent progress

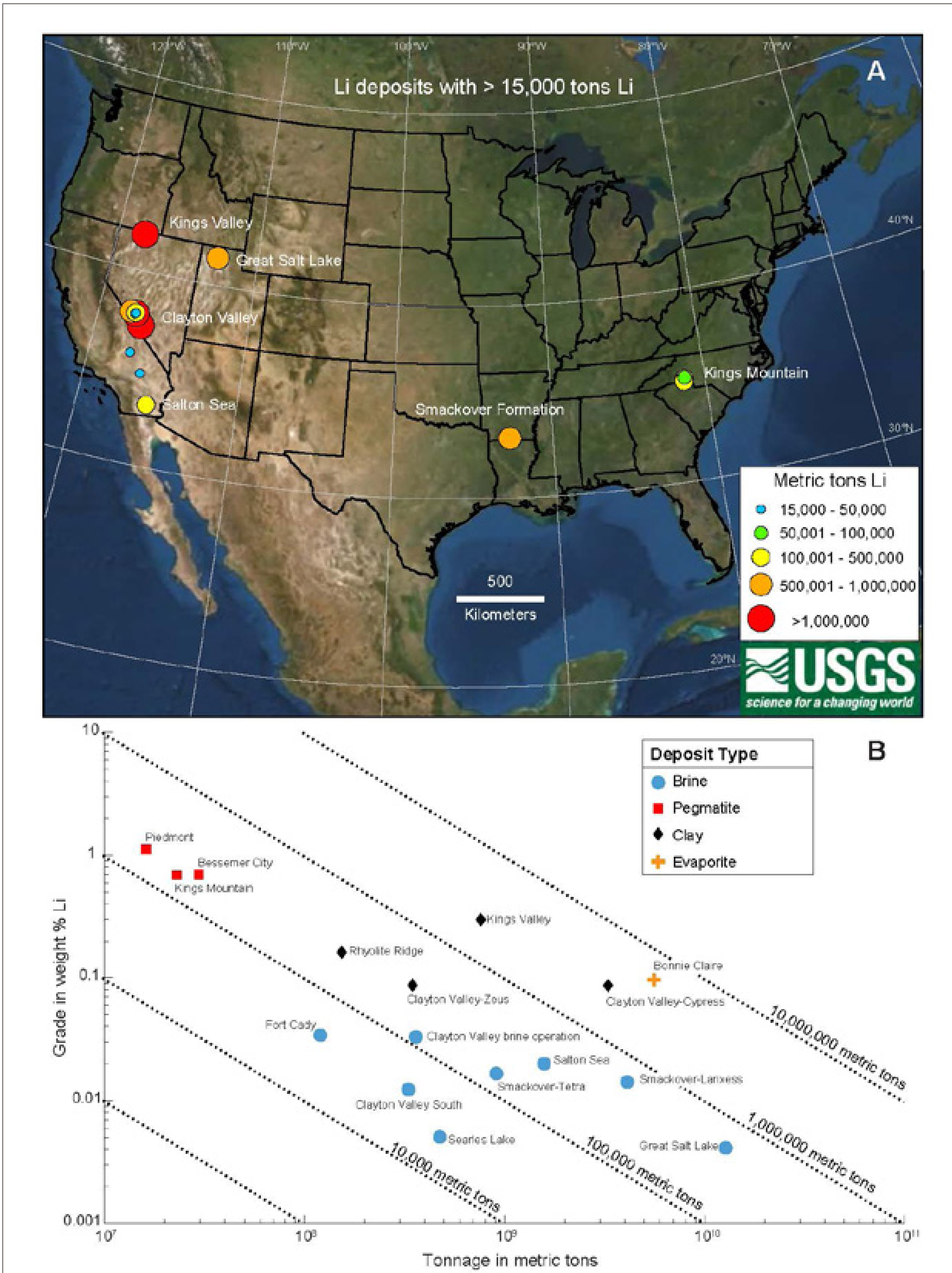
Assessment of the potential domestic primary supply of critical minerals requires development of new methodologies, new datasets and new and improved tools. In support of mineral resource research and the Earth MRI, the USGS is developing a mineral-systems approach to critical minerals inventory, research and assessment. A mineral system represents the geologic footprint of processes that came together in space and time to form a variety of genetically related ore deposits. Therefore, identification of one part of a large mineral system raises the possibility that related ore deposit types may be present nearby or under cover. Critical minerals occur in a variety of mineral systems of different types and ages that occur in different parts of the country. By delineating the possible extent of a given mineral system, target areas can be selected for detailed geologic mapping by state geological surveys and acquisition of new airborne geophysical surveys under Earth MRI.

Compilations describing rock outcrops and airborne geophysical data have provided new data on the Stillwater Complex, an important host for platinum-group elements in southwestern Montana (Parks and Zientek, 2019; Parks et al., 2019). Geochemical analyses of bauxite and associated rocks from central Arkansas, historically the most significant metallurgical-grade bauxite district in the United States, indicate that they lack the enrichments in rare earth elements, gallium and scandium that are present as byproducts in bauxites in some other parts of the world (Van Gosen and Choate, 2019).

The USGS has released a summary report on the first global assessment of undiscovered copper resources (Hammarstrom et al., 2019). Although copper is not on the list of minerals deemed critical under Executive Order 13817 (2017), copper deposits are the principal source of several critical mineral commodities that do occur on the list, such as cobalt, rhenium and tellurium, among others. The assessment report includes an atlas that shows the global distribution of areas that have identified resources and potential undiscovered resources for the two types of deposits that provide most of the world's copper: sediment-hosted deposits (a major source of cobalt) and porphyry copper

Figure 3

A. Map showing geographic distribution of lithium deposits with resources >15,000 t; B. Grade-tonnage plot of lithium deposits of various types in the continental United States. Diagonal lines represent equal cumulative volumes (Karl et al., 2019).



deposits. Porphyry copper mining produces about 80 percent of global rhenium supply and almost all selenium and tellurium (John and Taylor, 2016). Platinum-group metals, tungsten and uranium have also been recovered from some deposits as byproducts. Although the United States has significant identified porphyry copper resources, few mineral-processing operations currently recover these byproduct commodities. The report includes probabilistic estimates of amounts of undiscovered copper and estimates of what part of the in-place copper resource might be economic depending on depth, infrastructure and other considerations (Robinson and Menzie, 2012; Hammarstrom et al., 2019). A new study showed that although the southwestern United States, one of the world's premier porphyry copper provinces, is well explored, application of new tools such as satellite-based mapping of zones of alteration, indicates that additional undiscovered resources are likely (Mars et al., 2019). Future new porphyry copper discoveries as well as evaluation of the large amounts of mining waste at existing and historical mines represent potential domestic sources of some critical minerals.

New tools have been developed to facilitate USGS three-part mineral resource assessments, which consist of delineating permissive tracts for a given deposit type, using grade and tonnage models as analogs for the resources that could be present in undiscovered deposits and making probabilistic estimates of numbers of undiscovered deposits. MapMARK4, a new computer program, combines estimates of numbers of undiscovered deposits with grade and tonnage models to simulate a distribution of undiscovered deposits and their contained resources (Ellefsen, 2017a,b; Shapiro, 2018). Results from this program provides input to another new program, the Resource Assessment Economic Filter (RAEF) (Shapiro and Robinson, 2019). The RAEF program implements simple engineering mine model calculations based on user-supplied information on mine and beneficiation methods, mineral deposit type characteristics, simulated ore tonnage and grade estimates, undiscovered deposit depth profiles and regional cost features. The calculations evaluate the fraction of simulated deposits with tonnage and grade characteristics that provide a positive return on investment based on the engineering cost model analysis. This analysis provides an estimate of economic recoverable resources and an appraisal of the risk of failure as defined by the fraction of simulated deposits that are not economic.

The USGS has initiated a two-year project on mineral resource assessment methods to train the next generation of assessors. As part of the training, the participants are developing a new grade and tonnage model for tungsten deposits, conducting an assessment of domestic tungsten resources and applying the new assessment tools for the first time.

Mapping and geophysical surveys: Earth MRI

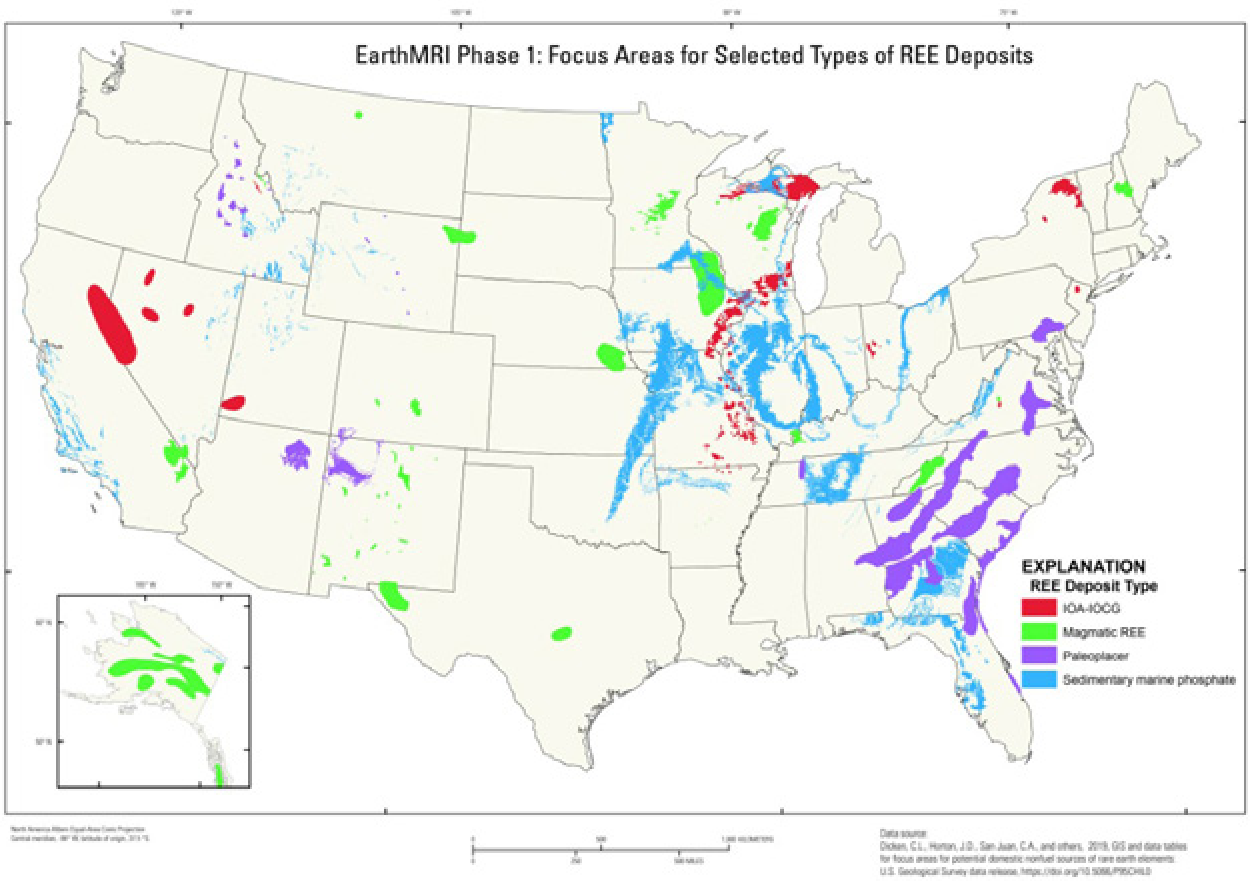
In fiscal year 2019 (FY19), the USGS established Earth MRI as a national effort to produce detailed geologic maps, airborne geophysical survey data and precision elevation (lidar) data for areas that have a high probability to host critical mineral resources (Day, 2019). The goal of this collaborative effort with the Association of American State Geologists is to improve our knowledge of the geologic framework in the United States (which has multiple societal benefits beyond mineral resources) and to provide essential information for areas with potential for undiscovered critical mineral resources to facilitate exploration efforts by the private sector. The outcome of the effort will be an enhanced understanding of the U.S. domestic mineral supply to help decrease our reliance on imported sources of minerals essential to the nation's security and economy.

Earth MRI is taking a phased approach toward evaluating areas for new data collection across the nation. The initial effort (phase 1) in FY19 was on mineral systems containing rare earth elements. Scientists from the USGS Mineral Resources Program undertook a qualitative nationwide evaluation to delineate general outlines of areas permissive for hosting the mineral systems that contain deposit types most likely to contain rare earth elements in sufficient quantity that, if the areas were developed, would result in an appreciable increase in the U.S. supply. The evaluation resulted in the definition of focus areas in which to acquire new geologic maps, airborne geophysical data, and elevation (lidar) data.

In 2019, the USGS released a report on the types of rare earth mineral deposits known to occur in the United States (Van Gosen et al., 2019) as well as a report and data release on focus areas for potential rare earth resources in the United States (Hammarstrom and Dicken, 2019; Dicken et al., 2019). Examples of the distribution of some mineral systems that may host rare earths in the United States are shown in Fig. 4. Iron Oxide Apatite-Iron Oxide Copper-Gold (IOA-IOCG) systems, such as those that host the rare earth element-bearing Pea Ridge deposit, are known in southeastern Missouri (Day et al., 2016) and in the Adirondack Mountains of New York

Figure 4

Map showing the distribution of four types of mineral systems that may host rare earth mineral resources in the United States. Note that these are very broad, generalized areas and targeted studies to identify new critical mineral resources have a much smaller footprint within a given system. IOA-IOCG, Iron Oxide Apatite-Iron Oxide Copper-Gold. Data from Dicken et al., 2019.



(Shah et al., 2019b; Taylor et al., 2019). Examples of magmatic rare earth element systems include the Mountain Pass rare earth deposit in southern California, an active mine, and the proposed Bear Lodge Project in Wyoming. An analysis of existing data identified several belts in Alaska that have potential for magmatic rare earth element systems (Karl et al., 2016). That study provided the template for identifying key areas for acquisition of new data through the Earth MRI project. Sedimentary marine phosphate deposits are widely distributed in some parts of the United States and in some places, have been shown to host rare earth elements in significantly elevated concentrations (Emsbo et al., 2016). Surficial weathering systems formed paleoplacer deposits of heavy mineral sands that are mined for titanium and rare earth elements along the Atlantic coast of the southeastern seaboard. New geophysical surveys, the identification of areas in need of high-quality lidar data and geologic mapping projects for selected areas within these broad mineral systems are underway as part of phase 1 of Earth MRI to identify prospective areas for new deposits.

Earth MRI followed up on USGS research in FY19 by funding 14 state geological surveys to initiate detailed geologic mapping campaigns across the conterminous United States and Alaska (https://www.usgs.gov/special-topic/earthmri). The target date for release of these maps is mid-2021. In addition to acquisition of the new geologic maps, geophysical surveys and lidar data, 30 state geological surveys were funded to preserve archived critical mineral data and drill core information and to make those data publicly available online, as required in the federal critical mineral strategy.

Acquiring and making publicly available modern, high-quality airborne geophysical data is core to the mission of Earth MRI. Five major geophysical surveys are underway in FY19, to be flown by private industry in focus areas in the eastern, central and western areas of the conterminous United States and in east-central Alaska. A new high-resolution regional airborne survey from Charleston, SC northwestward across the Fall Line (the boundary between igneous/metamorphic Piedmont rocks and Atlantic Coastal Plain sediments) targets heavy mineral sand (paleoplacer) deposits that contain titanium, zirconium and rare earth elements (Shah et al., 2019a). Another survey was flown in the central United States over the Illinois-Kentucky-Indiana fluorspar, lead, zinc, cadmium, germanium, silver and barite district and the adjacent ~270-Ma-old Hicks Dome thorium- and rare earth element-bearing peralkaline igneous complex. Another high-resolution magnetic and radiometric survey is being conducted in northern Arkansas in areas underlain by rare earth element-rich phosphate horizons. The intent of the survey is to map the aerial distribution of this important national source for heavy rare earth elements and provide a pilot study for geophysical mapping of other rare earth element-enriched phosphate units in the United States. Preliminary USGS research suggests this phosphate occurrence ranks as one of the largest and highest concentrations of heavy rare earth elements in the world (Emsbo et al., 2015; Emsbo et al., 2016). In the western United States in the southeastern Mojave Desert of California and Nevada (Fig. 4), a regional survey was flown over the geologic terrane that hosts the Mountain Pass rare earth element deposit. The Mountain Pass mine is currently the only major source of rare earth element production in the United States, and the likelihood of other undiscovered deposits in the region prompted the acquisition of a high-resolution airborne magnetic and radiometric data to supersede inferior, antiquated airborne data. The final survey, by the Alaska Division of Geological and Geophysical Surveys, targets the acquisition of new data in the central part of the Yukon-Tanana Uplands. Bedrock exposure in this part of Alaska is generally poor in areas below the tree line (approximately 1,070 m or 3,500 ft), thus the new aeromagnetic and radiometric data will be key to delineating the concealed geology to help evaluate the region for critical mineral potential.

The first geophysical data supported in partnership between Earth MRI and the USGS National Cooperative Geologic Mapping Program have been released for the southern Midcontinent region (McCafferty and Johnson, 2019; Phillips and McCafferty, 2019). Interpretation of these data provide insights into concealed mineral systems in a part of the country where surface mapping approaches are inadequate to define the extent of mineral systems (McCafferty et al., 2019a,b). The USGS conducted an inventory of airborne geophysical surveys for the United States that represents digital data for all magnetic and radiometric data for the country to provide the foundation for assessing data quality and identifying key areas for acquisition of new data (Johnson et al., 2019).

Phase 2 of Earth MRI, starting in FY20, is focused on delineating mineral systems throughout the United States that may contain nine additional critical mineral commodities or groups (aluminum (bauxite), cobalt, graphite, lithium, niobium-tantalum, platinum-group elements, tin, titanium and tungsten). Workshops were held in September and October 2019 that brought together more than 80 technical experts from the USGS and 29 state geological surveys. They identified focus areas for the phase 2 commodities, resulting in a series of priority areas to be funded for FY20 and FY21 geologic mapping, and geophysical and lidar surveys. Workshops are planned during 2020 that will address more of the remaining 35 critical mineral commodities, resulting in a planned workflow for new geoscience data acquisition for future campaigns.

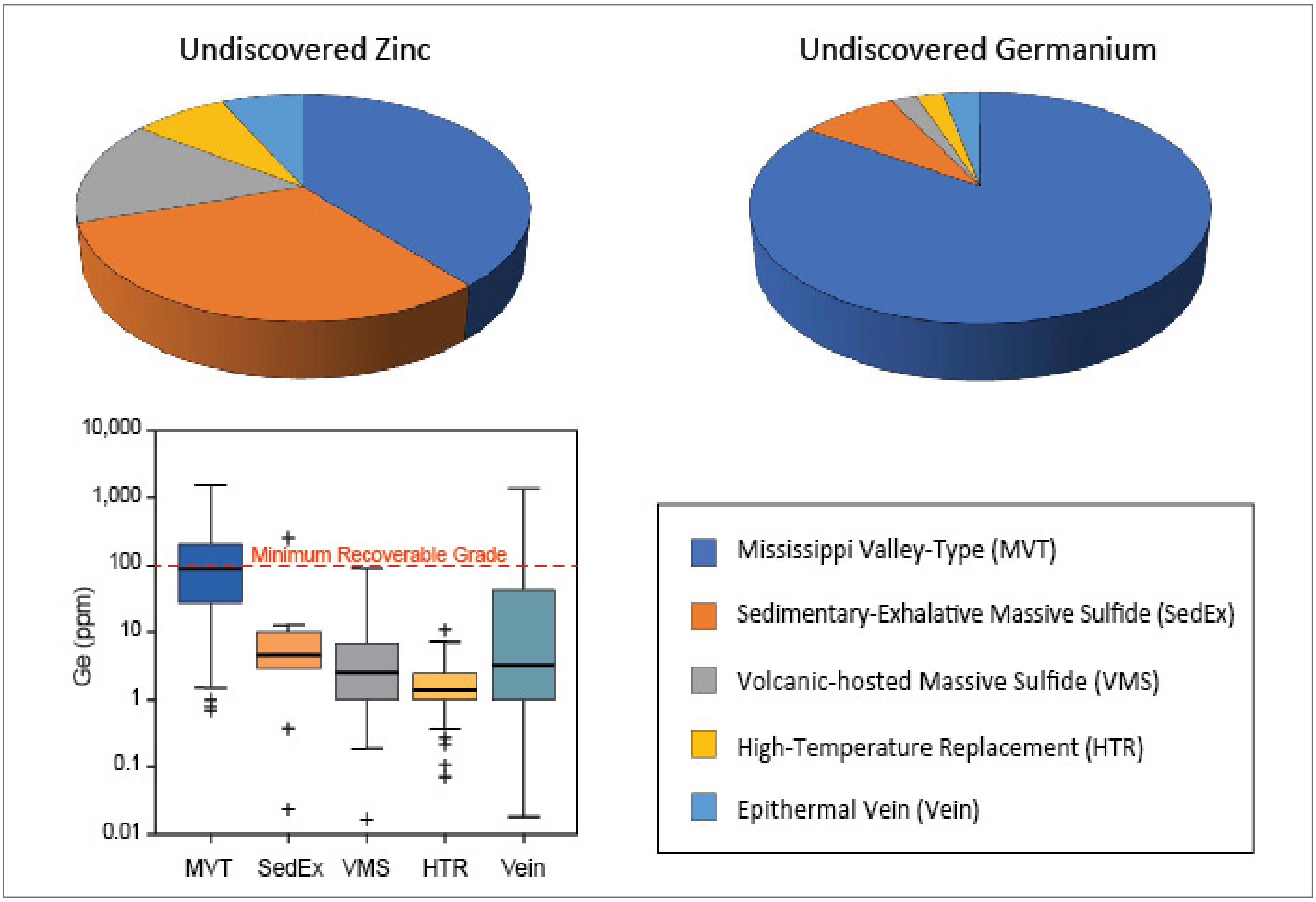
Mineral research: unconventional critical mineral resources

The demand for primary or coproduct critical mineral commodities, for example, rare earth elements, lithium and tungsten, is typically largely met by mining deposits for which the grades and tonnages of these commodities are the primary drivers of economic viability for a given operation. For these critical mineral commodities, increasing supply will rely on the discovery of new deposits or extensions of existing deposits. In contrast, the demand for byproduct critical minerals, such as germanium and tellurium, is met by mining deposits of primary commodities, such as zinc and copper, respectively. Because byproduct commodities do not dictate the economic viability of a mining operation, increasing their supply presents more of a challenge. Options include improving recovery at operations that currently recover these commodities, implementing recovery at operations with potential that currently do not recover these commodities, or reprocessing mine waste or other waste streams. Recycling may add to supply but will not eliminate the need to identify new sources. Currently, for example, about 30 percent of the germanium consumed globally is from recycled materials; however, this is in the form of new scrap produced during manufacturing, which does not add to supply (U.S. Geological Survey, 2020). The recycling of tellurium, in contrast, is very limited.

Germanium has important applications in fiber-optic technology as an essential dopant and as window material for infrared sensing systems. Tellurium has emerging demand in cadmium-telluride photovoltaic cells, which have some of the highest efficiencies among photovoltaic materials. Germanium and tellurium illustrate opposed behaviors for byproduct critical mineral

Figure 5

Pie charts showing the relative contribution of undiscovered zinc and germanium sources by deposit type. The box and whiskers diagram shows the concentration of germanium in sphalerite (modified from Frenzel et al., 2016). The Minimum Recoverable Grade is from Frenzel et al., 2014.



commodities in terms of their pathways through ore-processing circuits. Their opposing behaviors during ore processing are due, in part, to the minerals that host these critical minerals and how the ores are processed (i.e., whether they are associated with ore minerals or tailing minerals.)

Estimating the amount of undiscovered byproduct commodities is complex. The USGS conducts mineral resource assessments at scales ranging from regional to global. A national assessment of undiscovered deposits of gold, silver, copper, lead and zinc was conducted in 1998 (USGS National Mineral Resource Assessment Team, 2002). The national zinc assessment can be used to estimate the amount of undiscovered germanium because of the substitution and recovery of Ge from sphalerite — the primary zinc ore mineral in the United States. The national assessment estimated that there are 191 Mt (210,000,000 st) of undiscovered zinc in the United States in Mississippi Valley-type, sedimentary exhalative, volcanic-hosted massive sulfide, high-temperature replacement deposits and miscellaneous vein deposits (Fig. 5). This estimate can be used to estimate the amount of undiscovered germanium in the United States by combining these results with the germanium data for sphalerite — from (Frenzel et al., 2014, 2016) who reported trace element data by deposit type that were compiled from the literature (Fig. 5).

The sphalerite compositions vary significantly by deposit type with Mississippi Valley-type deposits having the highest median germanium concentration, followed, in decreasing order, by sedimentary-exhalative deposits, miscellaneous vein deposits, volcanic-hosted deposits and high-temperature replacement deposits. The combination of these mean values with estimates of undiscovered zinc deposits yields an estimate of undiscovered germanium in these zinc deposits of 20 kt (21,900 st). An interesting insight from this analysis is that the potential for future discoveries of zinc deposits in the United States should be dominated equally by Mississippi Valley-type and sedimentary exhalative deposits in subequal proportions, but the potential yield of germanium from these potential new discoveries will be dominated by the Mississippi Valley-type deposits because of the higher germanium content of their sphalerite. The potential contribution of germanium from deposits types other than Mississippi Valley-type deposits is further diminished the fact that 100 ppm germanium in concentrates has been suggested as a practical cut-off grade for recovery (Frenzel et al., 2014). Mississippi Valley-type deposits are the only ones that have consistently high germanium concentrations in sphalerite above this value. In other words, the probability of being able to recover germanium from these other deposit types is generally low but may be feasible on a case-by-case basis. The Red Dog sedimentary-exhalative deposit in Alaska is currently a source of byproduct germanium, but the germanium content of sphalerite there locally exceeds 100 ppm (Kelley et al., 2004). The consideration of an operational cut-off grade means that potential future undiscovered sources related to zinc mining will be restricted to a subset of producing zinc deposit types. The uneven endowment of germanium in sphalerite by deposit type narrows the options for future recovery of germanium as a byproduct of zinc mining.

Because of limitations on the potential for new sources of byproduct germanium, the recovery of germanium from mine waste streams — current and legacy — prompts consideration of other unconventional sources. The close association of germanium with sphalerite holds promise for recovery by processing legacy mine waste. At active zinc mines, germanium is strongly linked to sphalerite concentrates, and more than 90 percent of the germanium mined reports to the hydrometallurgical plant with the zinc concentrate. However, the potential for recovery may be more complicated due to the speciation and deportment of germanium-bearing minerals. As an example, the tri-state mining district in Oklahoma, Kansas and Missouri has historically yielded germanium as a byproduct. The Tar Creek Superfund site is within the district. The site was placed on EPA's National Priorities List in 1983 due to elevated lead and cadmium in mine waste and their leaching into local surface water and groundwater. Mine waste piles in the area contain bulk germanium concentrations that are up to 10 times higher than the average crustal abundance. Careful examination of the mine waste reveals not only sphalerite as a host of germanium, but also the zinc-silicate mineral hemimorphite ($Zn_4Si_2O_7(OH)_2{\cdot}H_2O$). In fact, germanium concentrations of hemimorphite reach 2,200 ppm whereas sphalerite contains a maximum of around 75 ppm (White et al., 2018) (Fig. 6). Hemimorphite is a common weathering product of sphalerite in siliceous environments and is one of the zinc ore minerals in supergene nonsulfide zinc deposits (Hitzman et al., 2003). Thus, a mine waste reprocessing strategy not based on a robust geometallurgical understanding of germanium host minerals would likely achieve poor recovery of germanium.

The behavior of tellurium during ore processing contrasts distinctly with that of germanium. The primary source of tellurium is from the mining of porphyry copper deposits, where it is recovered from the anode slimes. During ore processing, close to 90 percent of the tellurium in the ore is lost to the flotation tailings; only 4.5 percent of the amount originally removed as ore is recovered (Ojebuoboh, 2008; Kavlak and Graedel, 2013). At present, the host of the tellurium in the tailings is unclear but association with pyrite, either in solid solution or as inclusion of telluride minerals, is a likely candidate. If association with pyrite proves to be the case, the production of a pyrite concentrate at active porphyry copper mines and by reprocessing tailings at legacy sites could serve the dual purpose of mitigating the environmental footprint of tailings storage facilities and recovering a scarce critical mineral commodity.

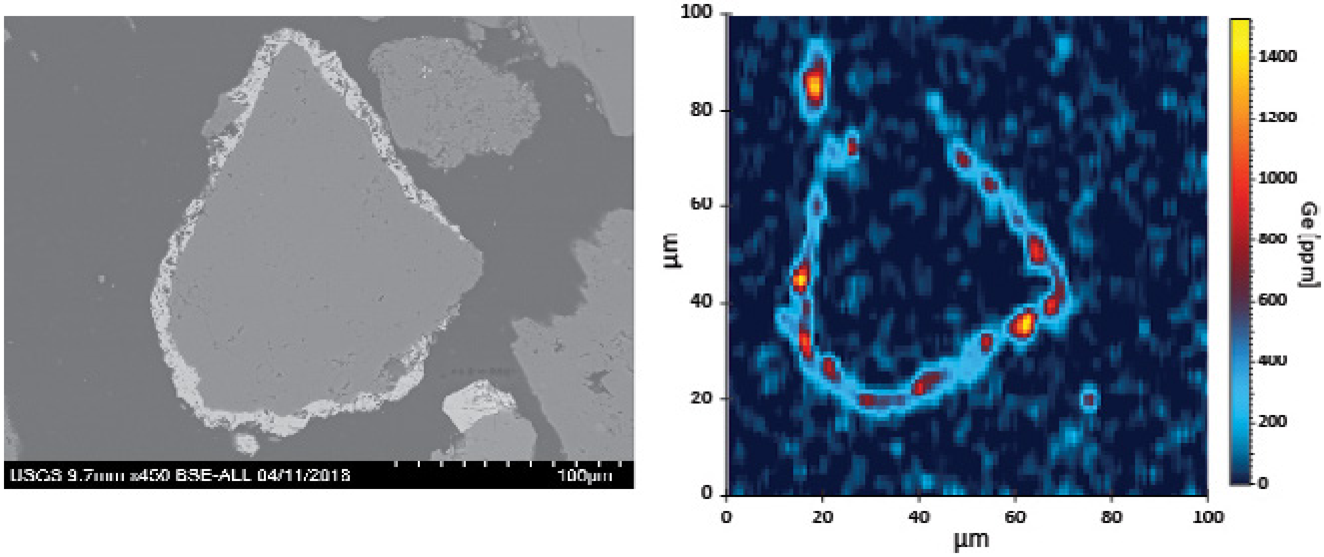
Other waste streams related to extractive industries may merit consideration as unconventional sources of critical minerals that could foster synergies between resource recovery and environmental mitigation. Coal ash from powerplants has received considerable attention as a potential source of rare earth elements (Franus et al., 2015). Likewise, phosphogypsum waste from phosphate mining and fertilizer production is known to have elevated concentrations of rare earth elements (Rychkov et al., 2018). Oil-field brines currently produce bromine and are being developed as a potential source of lithium, a key critical mineral commodity used in batteries (Standard Lithium, 2020). Hydraulic fracturing during oil and gas production already requires the handling of large amounts of subsurface brines. A variety of soluble critical mineral constituents may be recoverable as byproducts of oil and gas production.

Concluding remarks

Recent events have highlighted the risks of exclusive reliance on imported materials and products which depend on the smooth functioning of global supply chains. Secure supplies of critical mineral raw materials, and the resiliency of their supply chains, is of central importance to the economic and national security interests of the United States. The identification and responsible, sustainable development of abundant domestic mineral

Figure 6

The backscattered electron-scanning electron microscopy image on the left shows a quartz grain (medium gray) surrounded by a rim of hemimorphite (white) mounted in epoxy (dark) from a mine waste pile from the Tar Creek Superfund site in Oklahoma. The image on the right is a laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) map of the same grain showing the relative enrichment of germanium in the hemimorphite rim.



raw materials offers a clear opportunity to address the long-standing issue of increasing import reliance. The United States has addressed similar challenges before with oil and natural gas. The oil price shocks in 1973 and 1979 prompted the research and development that resulted in technological advances such as hydraulic fracturing and horizontal drilling, which transformed the resources contained in unconventional oil and gas deposits into economically viable reserves. American entrepreneurship and the willingness of the private sector to invest capital brought those reserves into production. As a result, we are far less dependent on imported sources to meet our energy needs and have become a net exporter, with attendant economic and national security benefits. While the list of minerals classified as critical is long, and their supply chains are often complex, the whole-of-government strategy that is currently being implemented identifies clear objectives to achieve results that are similarly transformational for mineral commodities. High levels of U.S. import reliance for mineral raw materials presents challenges which have taken decades to develop and can and must be addressed. The framework outlined in this paper identifies the elements of the federal critical mineral strategy and highlights the importance of domestic resources to achieve the overall goals of the critical minerals Executive Order. A sustained, focused and long-term effort to address the underlying issues is necessary to overcome these challenges. ■

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