USGS critical minerals review

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Issues related to the security of the supply of critical minerals have received increasing attention from the White House, Congress, U.S. government agencies and other interested parties for more than 15 years. More widespread awareness of the importance of critical minerals began in 2008 following the publication of the report *Minerals, Critical Minerals, and the U.S. Economy* (National Research Council, 2008). International news media subsequently highlighted the vulnerability of the rare earth element (REE) supply chain when China threatened to cut off supply to Japan over a territorial dispute in the East China Sea (New York Times, 2010). This event set in motion a chain of responses by the U.S. government, and those of other market economies, to address these concerns. Important steps in the United States included the development of a critical minerals screening methodology, led by the U.S. Geological Survey (USGS). This ongoing collaborative effort with several interagency partners is conducted under the auspices of the Critical Minerals Subcommittee (CMS) of the National Science and Technology Council (NSTC) in the Office of Science and Technology Policy (OSTP) at the White House Executive Office of the President (EOP) (National Science and Technology Council, 2016). This methodology has become steadily more quantitative, with the most recent work focusing on the economic vulnerability component of the model (McCullough and Nassar, 2017; Nassar et al., 2020a; Manley et al., 2022a, 2022b).

The critical mineral screening methodology provided a framework for the development of the first U.S. critical minerals list (Fortier et al. 2018; Federal Register, 2018) as directed by Executive Order (EO) 13817 (Federal Register, 2017). It was also one of the inputs that informed the development of the Federal Strategy for Ensuring the Secure and Reliable Supply of Critical Minerals, mandated by the same order (Federal Strategy, 2019). Much of the language and directives in EO 13817 were incorporated into the Energy Act of 2020 (Energy Act) and codified

Figure 1

Imports of refined copper for the period 2000 through 2022. Data from USGS (2021, 2023) (kt = thousand metric tons).

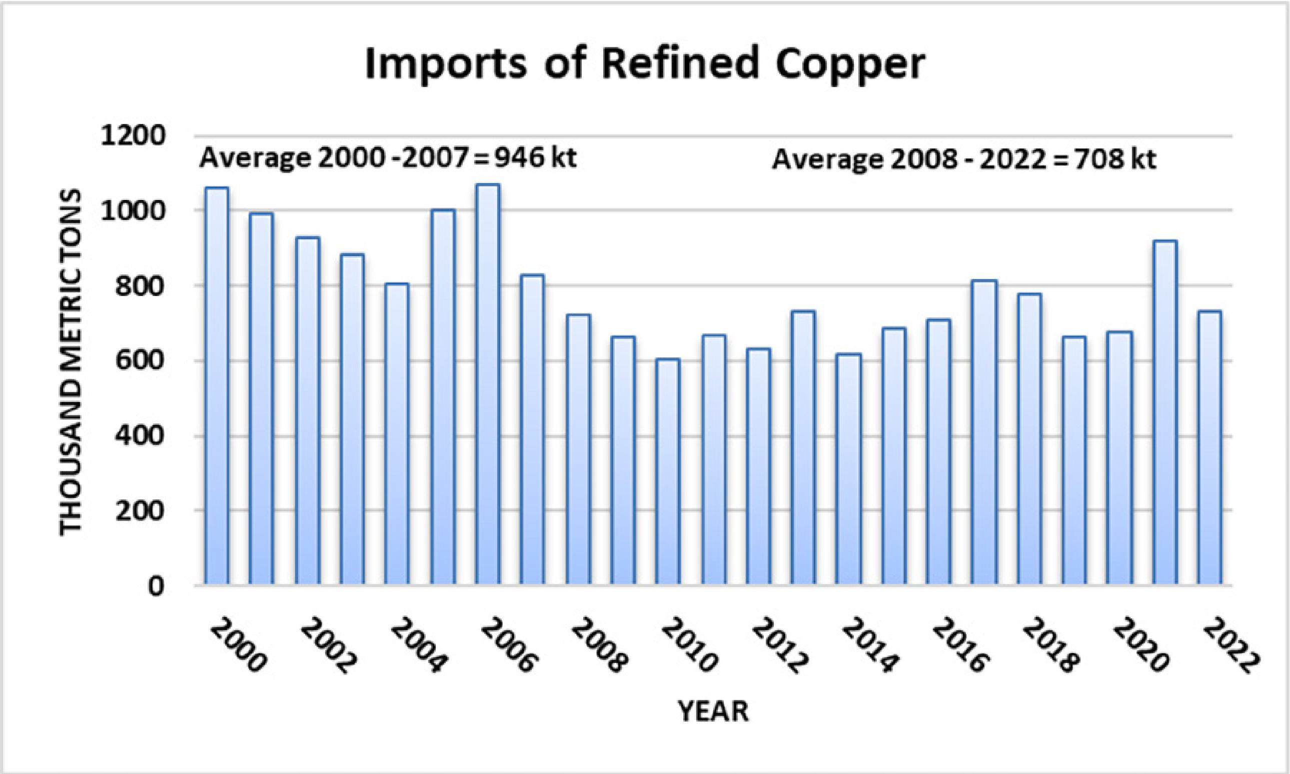
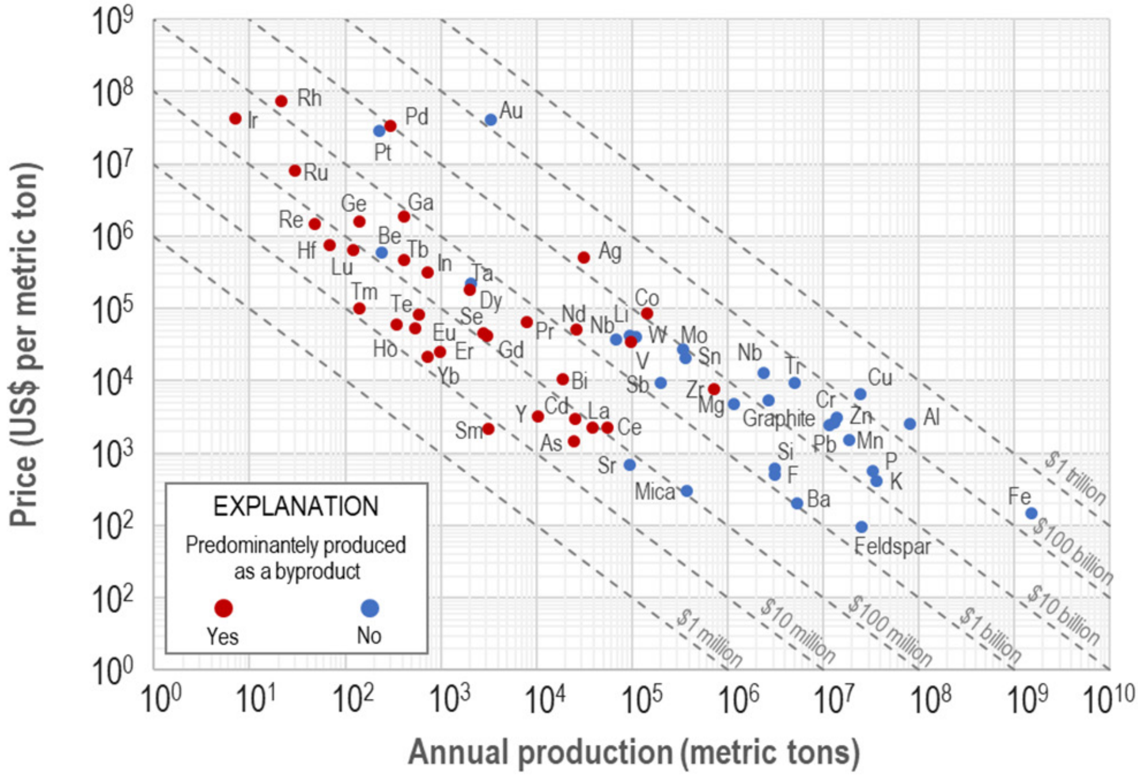


Figure 2

Log-log plot of annual production (in metric tons) versus annual average unit price (in U.S. dollars per metric ton) for 62 mineral commodities (identified by their elemental symbol or common name), circa 2018, based on information from Nassar and Fortier (2021). Diagonal lines represent constant monetary values at different intervals. See Nassar and Fortier (2021) regarding complexity and nuances of designating a critical mineral as a byproduct.



into statute. While the Energy Act directed (and in some cases authorized spending by) executive branch agencies, it did not appropriate funds to implement the objectives of the law. Additional executive orders (EO 13953 and EO 14017) and presidential determinations addressed specific issues relating to authorities and particular materials of interest (for example, rare earths and advanced battery materials). Appropriated funds, both regular and supplemental, have been brought to bear over the past two years, most notably in the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA).

There has been a steady progression from studies to executive actions, followed by legislation, first resulting in authorizations, and most recently, appropriations. Federal appropriations, in the form of awards and loans, are being leveraged by the private sector to establish domestic capacity through mechanisms such as the Defense Production Act Title III program and the Department of Energy Loan Program (Department of Defense, 2020; Department of Energy, 2022).

After years of advancing research and interagency coordination, these new policies and funding opportunities are helping to address supply-chain vulnerabilities, and support numerous geoscience advances in critical minerals, including:

- Updating the whole-of-government list of critical minerals.
- Modernizing the nation's mapping of mineral resources.
- Innovation in serving and interpreting the data.
- Enabling and accelerating new types of mineral resource assessments.
- Quantifying the nation's domestic mineral wealth, both still in the ground and in mine waste.

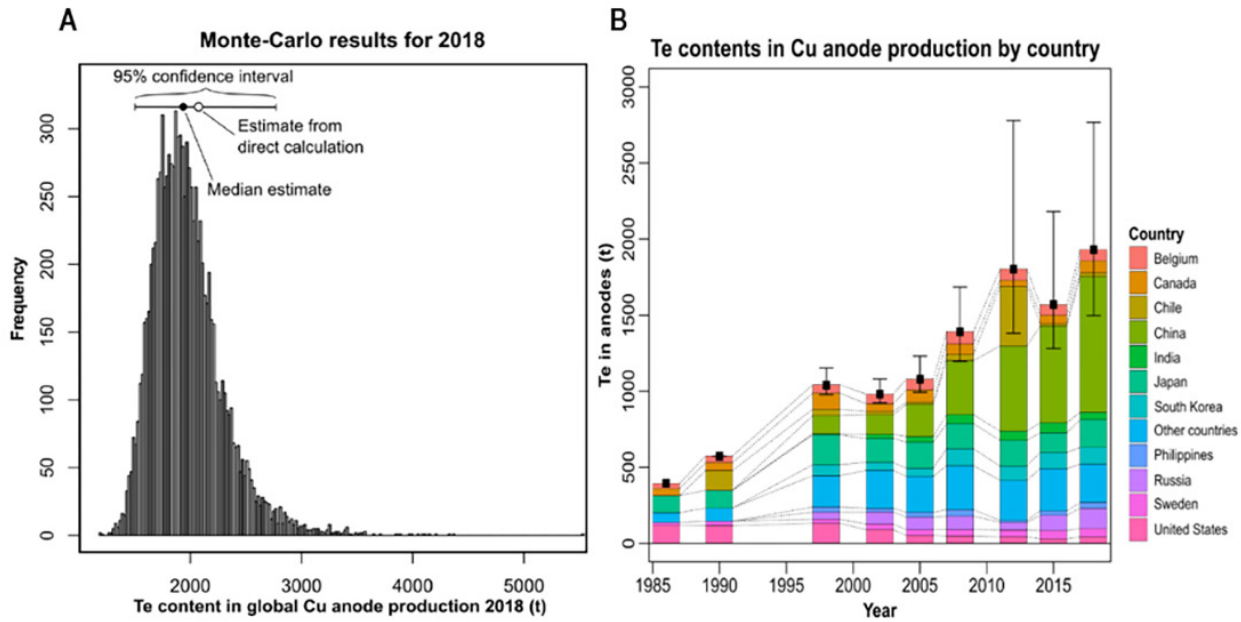
These efforts are directly informing federal strategies that prioritize domestic primary mineral development, domestic secondary mineral development through recycling and reprocessing waste, and strategic trade relationships with reliable partner nations.

U.S. list of critical minerals

For several mineral commodities, current sourcing (including domestic production and reliable trade arrangements) means that they

Figure 3

(A) Monte Carlo results indicating the probability distribution of tellurium contained in global copper anode slimes produced in 2018. (B) Modeled results for tellurium content of copper anode slimes by country and year with uncertainties (Nassar et al., 2022).



do not appear on the list of critical minerals — but their importance to the economy merits developing longer-term scenarios and projections through which to evaluate supply risk. One example is copper. The United States is a major producer of mined copper ores and concentrates, importing relatively small amounts of copper in this form. U.S. copper imports are dominated by refined copper which, after a recent spike in 2021, returned to prepandemic levels in 2022 and, in fact, are significantly lower than they were in the early 21st century (Fig. 1).

Refined copper imports averaged 946 kt/a (1,046 stpy) from 2000 through 2007, before the economic crisis in 2008; over the years since the economic crisis, refined copper imports have averaged only 708 kt/a (780 stpy). Despite the recent pandemic-related spike in imports in 2021, refined copper imports are not high by historical standards. Refined copper imported into the United States is predominantly from three countries: Chile, Mexico and Canada, listed in order of volume (USGS, 2023). All three countries have free-trade agreements with the United States (USTR, 2023) and hence would qualify as domestic content under the requirements of the IRA.

Copper is an essential mineral, not only in its own right but also as a source of several byproduct metals, many of which are on the critical minerals list. USGS is actively engaged in several aspects of the byproduct mineral challenge, such as material flow, mineral resource assessments and waste-product critical mineral potential as described in more detail in the sections below. The domestic copper industry is relatively robust compared to many of the other minerals on the critical minerals list. The United States has 25 mines where copper is recovered or processed, two smelters, two electrolytic refineries, and 14 electrowinning facilities. This domestic output stands in contrast to many other minerals of concern where the United States has virtually no production capacity (USGS, 2023).

The USGS is in the process of reviewing the critical minerals list as part of the normal cycle mandated in the Energy Act of 2020. Any revisions to the list will be the result of careful analysis of the most recent, complete sets of data, followed by peer review of the resulting conclusions, and will be issued through a public review and comment process in the Federal Register.

Byproduct mineral commodities

Many of the mineral commodities that are necessary for low-carbon energy generation and storage and other emerging technologies (for example, 5G wireless networks) are produced mainly or only as byproducts during the processing of other mineral commodities (Nassar et al., 2015). This includes cobalt in lithium-ion batteries for electric vehicles and consumer electronics; gallium, indium, selenium and tellurium, which are used in certain thin-film photovoltaics; and heavy rare earth elements that are used in permanent magnets for wind turbines, vehicle motors, air conditioners and consumer electronics. While some byproduct mineral commodities, such as cobalt, provide substantial value to producers, others like germanium, indium and tellurium provide limited monetary value. On a global scale, these commodities are produced in relatively low quantities (typically on the order of a few hundred to a few thousand metric tons per year), but unlike precious metals that also have low production quantities, their unit prices are not especially high. This is illustrated in Fig. 2, based on data from Nassar and Fortier (2021), which shows an inverse linear relationship on a log-log scatter plot between unit prices and production quantities, with minor mineral commodities generally occupying a lower region of the graph in relation to major mineral commodities and precious metals. Figure 2 also shows that the overall monetary value of their annual production is relatively small.

Examining these monetary values on a global scale may reveal the potential for investment risk. However, private-sector decisions on whether to recover certain byproduct mineral commodities typically consider the economics of individual operations. Consider a hypothetical electrolytic copper refinery that produces 300 kt/a (330,000 stpy) of copper cathode. Based on average reported tank house data, the refinery may have the potential to recover an annual average of 30 t (33 st) of tellurium from the anode slimes, which is where most of the tellurium reports — that is, very little goes to the cathode (Nassar et al., 2022). If the refinery recovered all this tellurium (and no other co- or byproducts), the value of the tellurium based on contemporary prices would represent less than 0.1 percent of the refinery's revenues, with the remaining greater than 99.9 percent coming from copper. Thus, the capital and operating expenses to recover tellurium or another minor mineral commodity may not be justified, especially if it has the potential to impact the production of the main, revenue-generating commodity.

These dynamics help explain why many minor byproduct mineral commodities are limited to a few producers. As a result of both these microeconomic factors, and national-level investments in specific supply chains, global production of these commodities is highly concentrated in a few countries (Nassar et al., 2020b), which increases their risk of supply disruption (Nassar et al., 2020a; Nassar and Fortier, 2021). Lists of "critical" minerals or raw materials are thus often populated with many byproduct mineral commodities (Blengini et al., 2020; Lusty et al., 2022; Nassar and Fortier, 2021).

While production of mineral byproducts is linked (by definition) to those of the host mineral commodity, it is not clear if and by how much that production can be increased without necessarily increasing the production of the host mineral commodities. Although many producers currently do not find the minor byproducts financially attractive, the potential to improve global recovery rates is likely high, but how high is it? In a recent study, Nassar et al. (2022) address that question for tellurium from copper electrolytic refineries. Using the best available data from tank house surveys and a Monte Carlo simulation, they show that, globally, the quantity of tellurium contained in copper anode slimes is roughly four times greater than the quantity that is currently recovered. They also indicate that while China has the largest potential to increase tellurium production, other countries including Canada, Japan, South Korea and the United States also have the potential to increase tellurium supplies. The results are summarized in Fig. 3.

In addition to notable recovery potential from the anode slimes, Nassar et al. (2022) reference previous works (Josephson, 2016; Ojebuoboh, 2008) that show that the vast majority (approximately 90 percent) of tellurium that is contained in the mined copper ores is lost to tailings, resulting in an overall recovery efficiency (from tellurium contained in the mined ores to a high-purity tellurium product) of less than 2 percent. Given the large flows of tellurium to tailings, it may be interesting to consider them as a future supply source. As illustrated in Fig. 4, the concentration of tellurium flowing into the tailings is, however, thought to be very low (0.01 to 0.3 parts per million) (Moats et al., 2021). While historical mine tailings may contain elevated levels of tellurium (Hayes and Ramos, 2019), there are likely numerous mineralogical, technological, social and legal challenges and complexities that may make its recovery difficult. Some of these complexities of recovering critical minerals from waste streams are being addressed by USGS research, as described below. For tellurium, however, the most accessible and likely the most economic source of tellurium from copper production thus remains in copper anode slimes.

Studies on gallium, germanium and indium show similarly large losses of these minor byproduct mineral commodities at different production stages from different sources (Frenzel et al., 2016b; Frenzel et al., 2016a; Frenzel et al., 2017; Licht et al., 2015). Utilizing data from Frenzel et al. (2017), as well as historical production data from the USGS (2021, 2023), Fig. 5 shows that the ratio of gallium-to-bauxite global production (solid line) has been much lower than the ratio of these elements in the ore. The data indicate that there is significant potential to increase gallium's global primary production from bauxite. Indeed, while the gallium-to-bauxite global production ratio has increased by more than an order of magnitude in the last few decades, it still has the potential to be increased by at least another order of magnitude. Frenzel et al. (2017) report similarly high potential to increase germanium supplies. In contrast, while the ratio of indium-to-zinc production is also well below the ratio of these elements in the ore, the potential to increase it further is much lower (perhaps only another two- to three-fold increase is possible) than that of gallium, germanium or tellurium. A quantitative assessment of the potential to increase the primary supply of other minor byproduct mineral commodities would be needed along with a better understanding of the technological and economic barriers to make such increases possible.

Earth MRI update

The USGS launched the Earth Mapping Resources Initiative (Earth MRI) in 2019 to modernize the surface and subsurface mapping of the United States. The Bipartisan Infrastructure Law (Infrastructure Investment and Jobs Act) funding is accelerating Earth MRI with an additional $320 million over five years, focused on identifying areas that may have the potential to contain critical mineral resources — both resources still in the ground and resources in mine waste. Earth MRI is a partnership with state geological surveys, other federal agencies and the private sector. The USGS and state geological surveys conduct geologic and reconnaissance geochemical mapping and produce interpretive reports of newly collected data. Earth MRI is also acquiring large regional airborne magnetic and radiometric surveys and focused electromagnetic surveys, along with lidar data in areas lacking such coverage. The applications of Earth MRI geoscience data and scientific interpretations go well beyond mapping critical mineral resources. The results are also being used to characterize geothermal energy resources, water resources, and to delineate areas prone to landslide, earthquake and flooding hazards.

In 2022, Earth MRI launched the mine-waste inventory and characterization called for in the Bipartisan Infrastructure Law, initiating pilot studies and broader partnering on nonfuel mine-waste materials. Since its inception in 2019, Earth MRI has funded 66 geologic and geochemical mapping projects with state geological surveys and 12 lidar surveys. Cumulatively, Earth MRI has contracted for 27 geophysical surveys, which has almost doubled the amount of high-quality magnetic data for the conterminous United States and quadrupled that for Alaska, covering an area approximately the size of Texas.

In partnership with state geological surveys, the USGS completed efforts to define focus areas for 23 mineral systems throughout the United States that could potentially host mineral deposits containing critical minerals as shown in Fig. 6a. These focus areas provide an initial, broad screening tool for targeting areas for new data acquisition (Dicken et al., 2022; Hammarstrom et al., 2023). The summary map shown in Fig. 6a and accompanying data in Dicken et al. (2022) provide a wealth of information on known deposits and geoscience information for critical mineral resources.

The focus areas are broad areas that contain lithologies that may contain critical minerals. They are used as guides to where more information and mapping are needed to refine the mineral potential for a given critical mineral commodity. An example of the application of focus areas for mafic magmatic mineral systems is shown in Fig. 6b, identifying broad areas within which deposits containing the critical minerals cobalt, nickel, chromium and platinum-group metals are known to occur, or could occur at depth or in places that have not been thoroughly evaluated for these types of mineral deposits.

Recent work in the Kentucky-Illinois fluorspar district and the Hicks Dome ultramafic intrusive complex located in southern Illinois, western Kentucky and southwestern Indiana demonstrates one of the goals for Earth MRI in developing an integrated geoscience data portfolio that facilitates modern geologic framework investigations. These studies are supported through geologic and geochemical investigations, airborne magnetic and radiometric surveys, and lidar data to help understand the regional geologic framework, location of known resources and mining history of this complex mineral district.

Detailed airborne magnetic and radiometric data were identified as critical to delineating the buried geologic and structural setting for the region. USGS geophysicists have led a sustained campaign to acquire modern, detailed airborne magnetic and radiometric data over the iron oxide apatite/iron oxide copper-gold and lead-zinc districts in southeast Missouri as well as the Illinois-Kentucky Fluorspar District, Hicks Dome area and associated mineral districts in southern Illinois, western Kentucky and southwestern Indiana (McCafferty, 2016a, 2016b; McCafferty and Johnson 2019; McCafferty and Brown, 2020; McCafferty and Connell, 2022). In addition, an Earth MRI-funded airborne magnetic and radiometric survey is being flown over a large part of Arkansas and southern Missouri (Fig. 7) that continues to add to our published data, enhancing our understanding of the southern midcontinent. These data and subsequent interpretations are leading to a new understanding of the three-dimensional crustal architecture of this important mineral-rich and seismogenic region (Lawley et al., 2022; McCafferty et al., 2016, 2019; McCafferty, 2022).

Denny et al. (2020) produced a detailed report and 1:50,000-scale map of the Illinois part of the Illinois-Kentucky Fluorspar District and companion detailed geologic map and report of Hicks Dome (Denny et al., 2021). The report includes information on noteworthy mineralization and resource calculations as well as the stratigraphy and geochemistry of the important rock units. Geochemical analyses for these projects, as well as for all Earth MRI projects, are published in periodic data releases (USGS, 2022). These products provide a wealth of information on the geologic setting, past mining and production history, and origin of the ore deposits. In addition to being an important source of fluorspar, lead and zinc, the district hosts the Midwest Permian Ultramafic District, including the Hicks Dome ultramafic igneous and breccia complex.

Lukoczki et al. (2022) of the Kentucky Geological Survey (KGS) recently released a regional geologic map of the Western Kentucky part of the Illinois-Kentucky Fluorspar District. The report and associated geologic map and data provide an in-depth review of mineral and rock specimens and KGS archived files. The work describes 39 probable igneous dikes that may be an economically viable source of REEs identified using a filtered aeromagnetic dataset provided by McCafferty and Brown (2020). These features were incorporated into a 1:50,000-scale geological map for the Western Kentucky Fluorspar District. The geochemistry of the newly identified igneous dikes shows elevated total REE concentrations. The various types of igneous dikes include alnöite, aillikite and rocks in which carbonate alteration predominates. The relatively high REE content in one massive calcite vein (280 ppm) suggests remobilization of REEs and warrants further study of fluid–rock interactions to better understand the mineral system of the Illinois-Kentucky Fluorspar District.

Ongoing efforts are underway by the Illinois State Geological Survey (ISGS) and KGS to integrate the recently published data and reports of the Illinois-Kentucky Fluorspar District and surrounding area. The goal is to better understand the resource potential for several known and suspected important base and critical mineral-bearing deposit types that include REEs, cobalt, barite, fluorspar, beryllium, uranium, strontium, gallium, germanium, indium and titanium. Additionally, the district is prospective for noncritical thorium, lead, zinc, silver, cadmium, and copper. The ISGS and KGS are developing three-dimensional geologic and geochemical models of the area. The modeling effort is a review of published data, integrating subsurface well, structural, geophysical, geochemical, mineralogical and historical mine footprint data to better understand the mineral endowment and regional geology. In addition, the KGS is compiling existing and new data on ultramafic alkaline igneous rocks that intrude the Paleozoic sedimentary strata that are likely to be genetically linked to epithermal fluid mixing associated with mineralization in the district. Furthermore, the KGS is refining the stratigraphic framework and correlation of the Ordovician and Devonian shales in the areas that are permissive for critical mineral accumulations. The goal is to explicitly connect the geologic maps to stratigraphy and to subhorizons that are likely to host REEs and other critical minerals in the shales. USGS scientists are following up with these studies to better understand the origin of ores at Hicks Dome and other similar alkaline igneous complexes (Andersen et al., 2020, 2021; Bennett et al., 2022).

Research on byproduct critical minerals

USGS Mineral Resources Program research on critical minerals continued in 2022 with an emphasis on byproduct critical minerals and mine waste as a potential source. Recent investigations on germanium related to zinc deposits in the Tri-State district including northeastern Oklahoma (White et al., 2022) demonstrated the importance of understanding the behavior of trace elements during the weathering of mine waste and how weathering processes redistribute germanium to secondary minerals formed during weathering. The weathering of sphalerite — the original source of germanium — in the chat piles (a mixture of historical gravity-separated gravel and traditional flotation tailings) produced secondary hemimorphite, a hydrous zinc silicate mineral that was found to sequester a higher concentration of germanium than the original sphalerite. This result highlights the fact that any strategy to reprocess the waste to recover germanium depends on understanding the current distribution of this commodity between the primary and secondary minerals of the waste material.

The Tri-State district project and related studies elsewhere have highlighted the challenges in characterizing the hosts of byproduct critical mineral commodities in ore and mine waste.

These byproduct elements commonly occur in trace minerals, or in trace quantities in more common minerals. In addition, their compositions can display complex zoning, their solid-solution mechanisms may require coupled substitutions with other elements, and many can occur in multiple oxidation states, which adds further complexity to substitutional mechanisms.

These intricacies mean that no single analytical method will yield all required information for ore genesis, ore processing or mine-waste reprocessing studies. Instead, multiple analytical techniques that span the spectrum from traditional techniques to more advanced, cutting-edge methods are needed to yield the desired insights, often in an iterative approach. The USGS has developed a streamlined workflow of mostly nondestructive techniques to understand the occurrence of critical minerals in ores and mine waste (Hayes et al., 2023), as shown in Fig. 8. The workflow, initially developed to better understand germanium in sphalerite, is being more broadly applied to several byproduct critical mineral commodities including cobalt, gallium, indium, nickel, tellurium, tin, tungsten and selenium, in a variety of sulfide and nonsulfide mineral hosts.

The workflow begins with traditional optical microscopy, with both transmitted and reflected light as appropriate. Scanning electron microscopy (SEM) follows, which permits finer detail to be discerned and greater information about compositional variations among mineral grains. Automated mineralogy, using advanced software integrated with SEM in systems, enables automated searches for rare minerals in samples that may host byproduct critical mineral commodities. A cathodoluminescence detector added to an SEM provides rapid, unparalleled qualitative insights into cryptic trace-element zonation in responsive minerals. Electron microprobe analysis (EMPA) — a traditional approach — provides quantitative information about major, minor and trace element compositions. However, laser ablation inductively coupled plasma mass spectrometry may yield better results for some of the critical mineral commodities because their concentrations can commonly extend down to the limits of detection for EMPA. Cutting-edge synchrotron-based techniques, such as in situ X-ray diffraction, X-ray fluorescence mapping and X-ray adsorption spectroscopy, provide unique information, much of which is not available from other techniques. For example, X-ray adsorption spectroscopy can be used to determine the valence (oxidation) state of many elements. As noted above, critical

Figure 4

Log-log plot of estimated annual flows of contained tellurium (horizontal axis) versus tellurium content of those flows (vertical axis) with uncertainties based on data reported by Josephson, 2016; Moats et al., 2021; Nassar et al., 2022 (Cu_2Te = copper telluride).

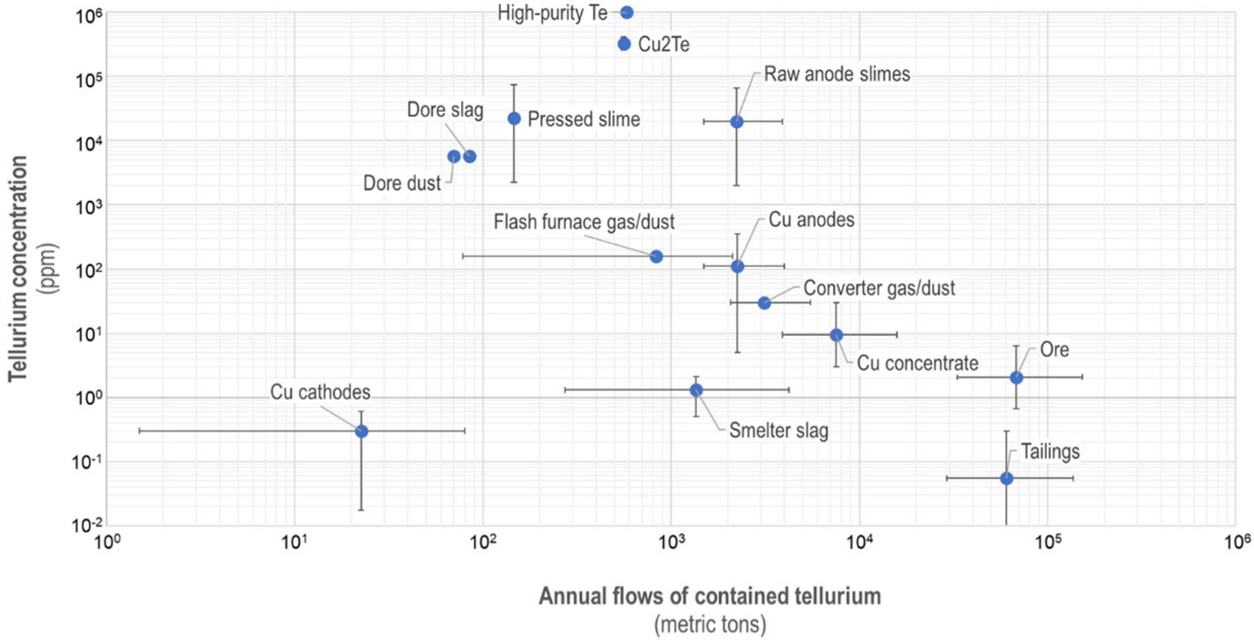
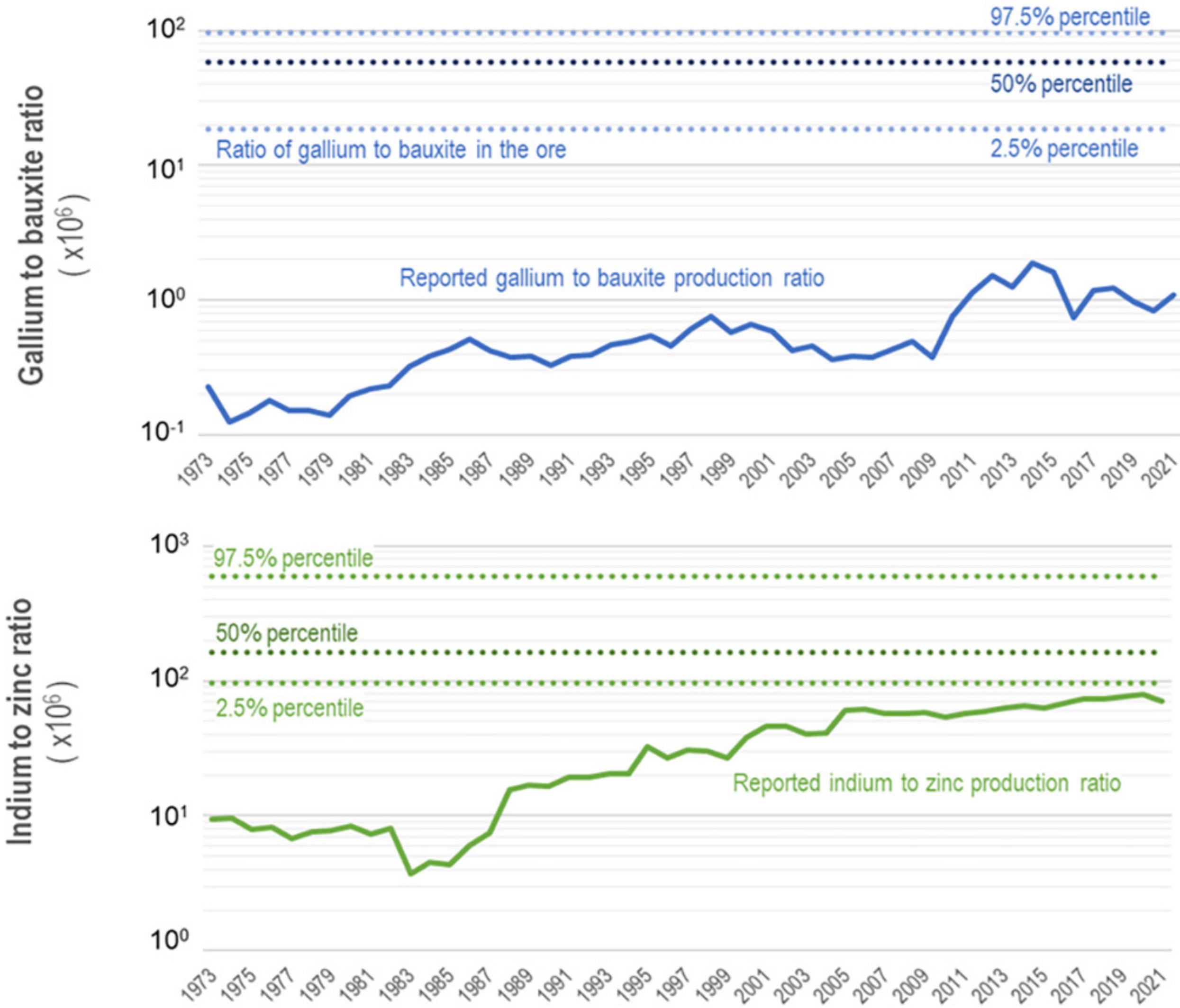


Figure 5

A time-series log plot of gallium-to-bauxite (top) and indium-to-zinc (bottom) production ratio from 1973 to 2021, with estimated dotted lines representing the 2.5 percent, 50 percent and 97.5 percent confidence interval for the ratios of these elements present in ores based on data from Frenzel et al. (2017) and the USGS (2021, 2023).



elements can occur in multiple oxidation states. The oxidation state of a critical mineral commodity influences its source, transport and fate in ore-forming environments, its weathering behavior in the surface environment, and its metallurgical processing.

The USGS has conducted a literature review of the exposure mechanisms and toxic effects of critical mineral commodities relevant to humans and surrounding ecosystems, in part to better inform their environmentally responsible recovery and handling (Jenkins et al., 2023). This initial literature review focused on nutritionally essential critical elements (cobalt, chromium, manganese, nickel and zinc) and the REEs. Improved knowledge of exposure pathways and adverse outcome pathways will lead to more effectively environmental management at mine sites and processing facilities as society seeks to meet its growing demand for critical minerals.

Under the BIL-funded focus on critical mineral potential in aboveground settings, the USGS and state geological surveys are conducting mine-waste characterization studies at sites that may have potential for critical minerals and assist in the development of a national mine-waste inventory. The first year of the program (2022) focused on developing a set of standard operating procedures and analytical methods to ensure that a nationally comparable dataset emerges from this effort. Three states were enlisted to help in this effort: Colorado, Florida and New Mexico. In 2023, the effort plans to expand to additional states with a focus on mill tailings and water sources that represent long-term liabilities, such as draining mine tunnels and large pit lakes, many of which require active treatment. The USGS's USMIN database has more than 5,500 features

Figure 6a

A map showing focus areas for 23 mineral systems that could host critical mineral resources in the United States and Puerto Rico (Hammarstrom et al., 2023; Dicken et al., 2022). The number of identified focus areas for each mineral system is shown in parentheses.

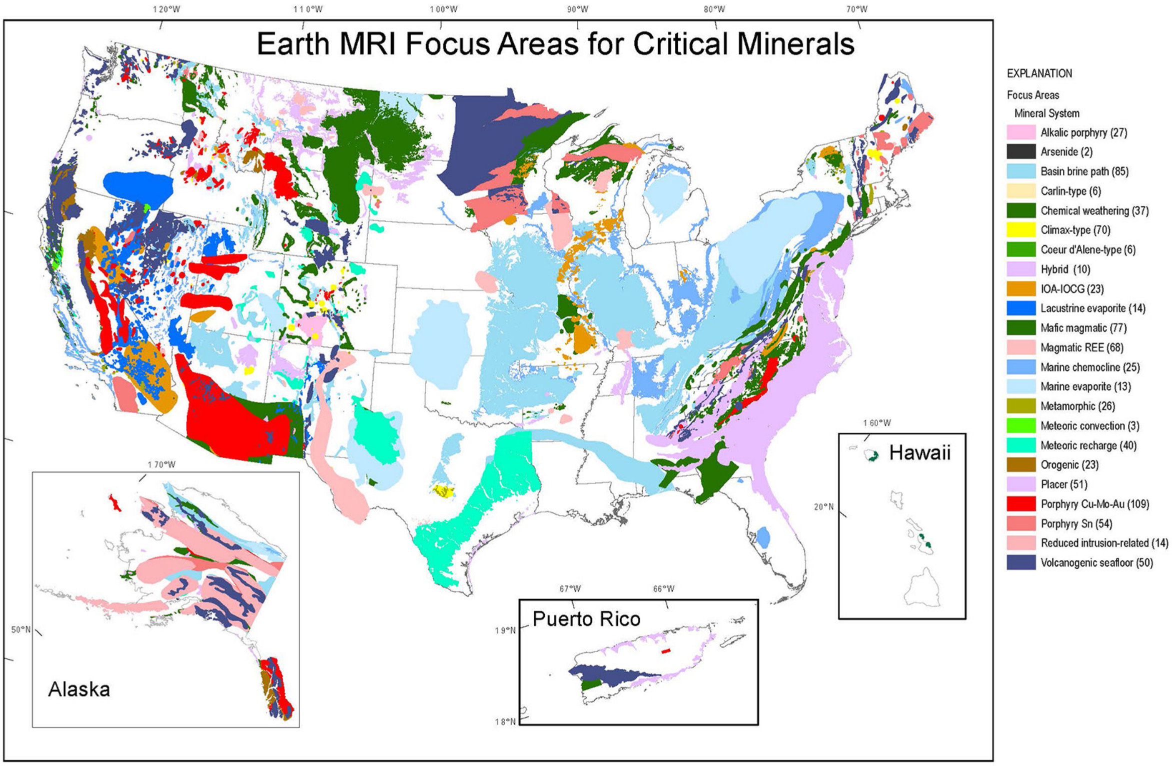
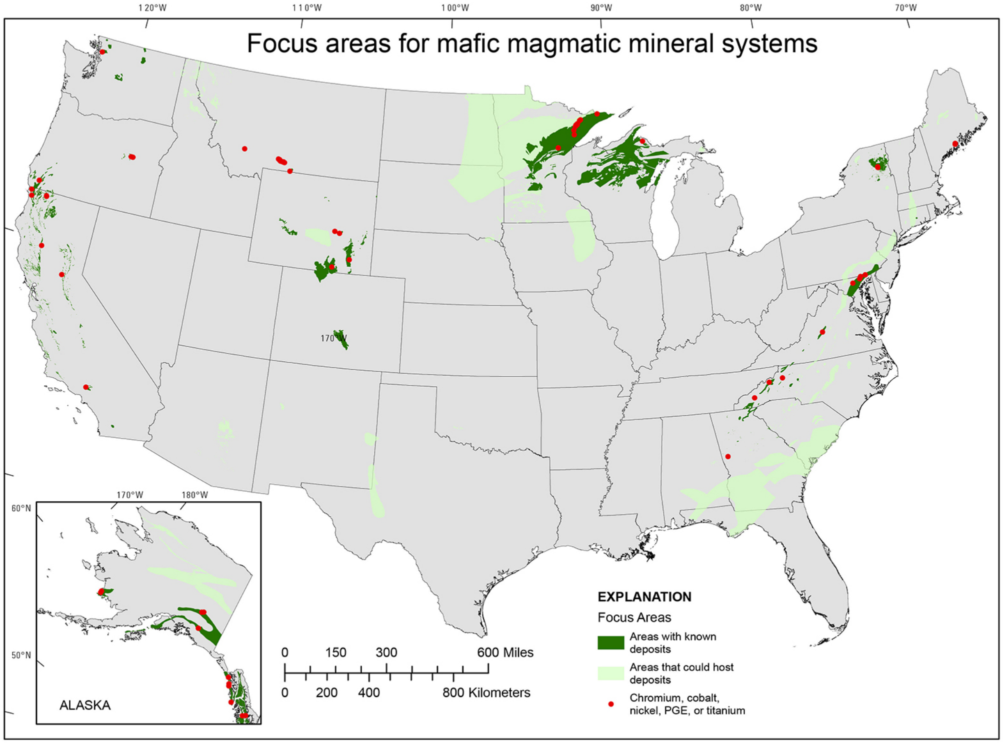


Figure 6b

A map showing focus areas for mafic magmatic mineral systems that could host cobalt, nickel, chromium and platinum-group metals in the United States. Focus areas from Dicken et al. (2022). Known deposits shown as red dots.



in the United States identified as mill tailings. The areal footprints of these tailings range from as small as 130 m^2 to almost 23 km^2, as shown in Fig. 9 (Horton and San Juan, 2016). However, 90 percent of the areal extent of these is found in the upper quartile of the identified features, which can help guide site selection for mine-waste characterization projects by the states.

International collaboration

The USGS maintains active international collaborations that support the identification of options to mitigate strategic and critical mineral resource vulnerabilities in line with recent U.S. governmental policy guidance discussed in the introduction of this paper. The Critical Minerals Mapping Initiative (CMMI) is an ongoing example of such a collaboration with Geoscience Australia and the Geological Survey of Canada. The broad goals of this effort, initiated in 2019, are to advance understanding of critical mineral resources in the three partner countries, Australia, Canada and the United States (Kelley, 2020; Kelley et al., 2021; Emsbo et al., 2021). Through data and expertise sharing, CMMI partners can advance critical minerals science.

A unified Critical Minerals in Ores (CMiO) (Geoscience Australia, 2021) database (for example, Fig. 10) has been built to advance our collective understanding of critical mineral abundances in mineral systems and deposit types using the classification scheme of Hofstra et al. (2021). The CMiO database is being augmented with geochemical results released by the USGS (Granitto et al., 2021) and Geological Survey of Queensland. To fill in data gaps in the CMiO database, the trinational partners are actively seeking contributions from external sources, with a particular focus on obtaining geochemical data on deposits in foreign countries. The goal of this, and future updates to the CMiO global digital database is to progressively build a more holistic view of critical mineral distributions across systems and deposit types in partner nations and elsewhere around the globe.

The CMMI collaboration is also focused on the evaluation of critical mineral prospectivity and assessment methods that (1) combine geological, geophysical and temporal datasets, and (2) incorporate findings from the CMiO database. The primary focus remains on prospectivity modeling for basin-hosted Zn-Pb deposits (Mississippi Valley-type and clastic-dominated Zn-Pb) because these deposits, found in all three partner nations, can host significant concentrations of Zn and other critical minerals, such as Ga, Ge and In. Knowledge-driven modeling efforts and national-scale data layers used in the models are nearly complete for Zn-Pb deposits in siliciclastic-mafic and-carbonate systems (Coyan et al., 2022). Initial phases have begun to develop mappable criteria for Zn-Pb deposits in Mississippi Valley-type systems. This effort expands on the general methodology of Emsbo (2009) and others. Our collaboration has demonstrated empirical spatial associations of these mineral systems with features observed in geophysical and geochemical datasets (McCafferty, 2022). These relationships reduce the exploration search space and highlight areas of high prospectivity for Zn-Pb deposits (Huston et al., 2022). In the future, CMMI anticipates that

Figure 7

Footprint of USGS airborne magnetic surveys for the southern midcontinent. Areas shown in rainbow colors indicate published datasets, and the area in light gray represents an in-progress survey in spring 2023. All published data are available at Earth MRI (2023).

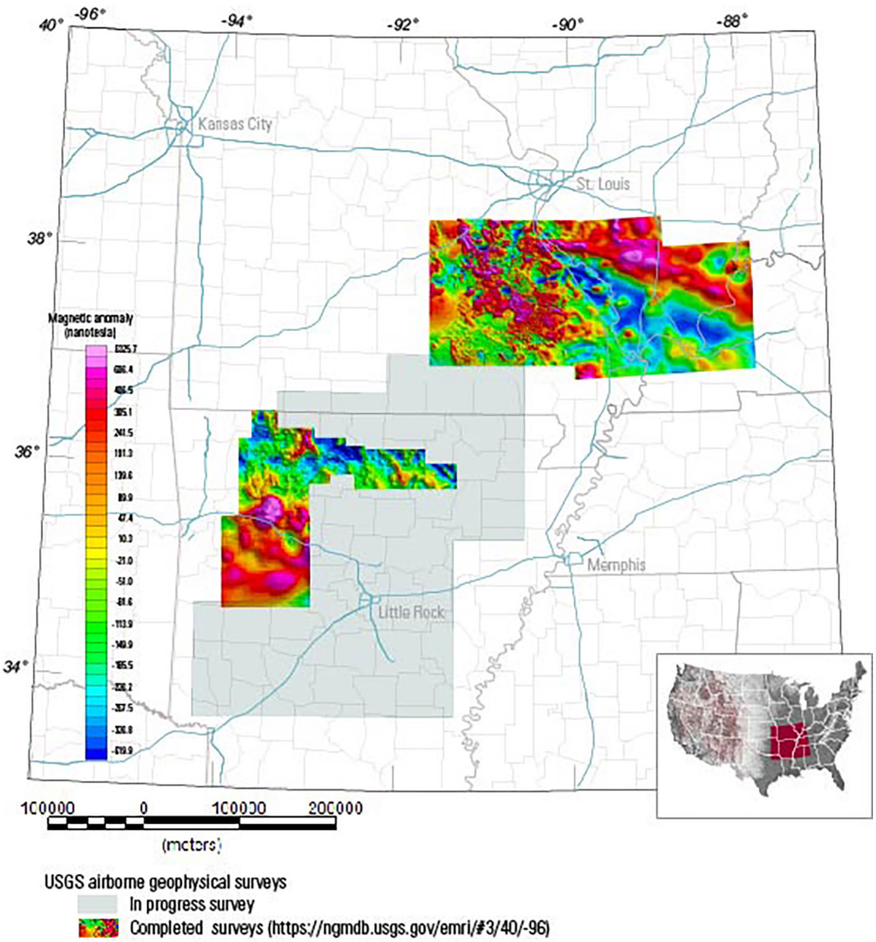
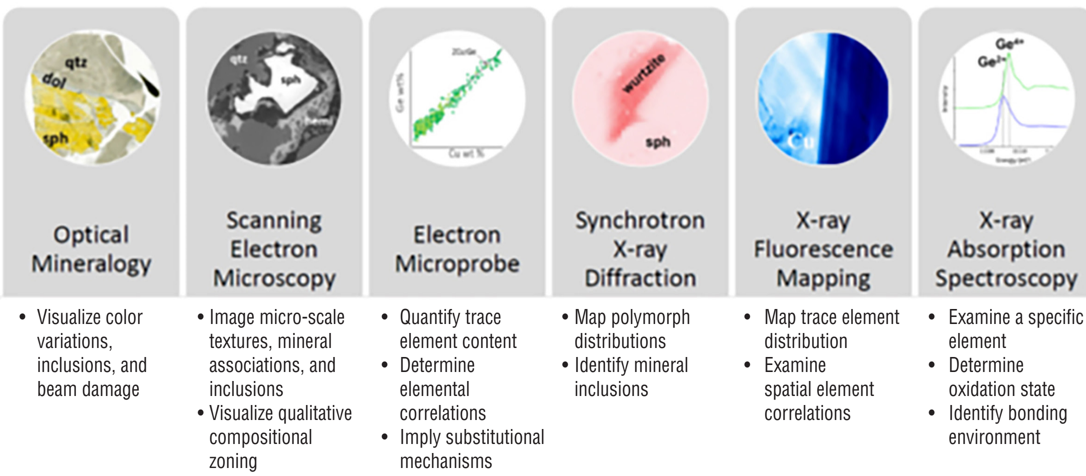


Figure 8

Schematic diagram showing the streamlined workflow to investigate critical mineral hosts in ore and mine-waste samples. Modified from Hayes et al. (2023).



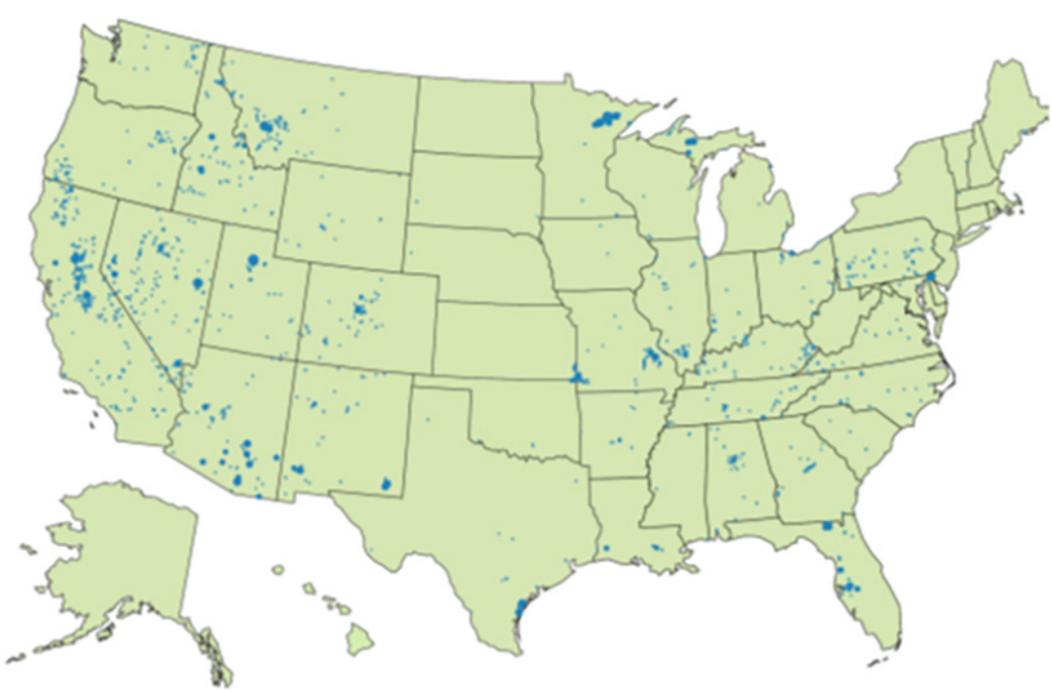
it will develop similar mappable criteria for the spectrum of deposit types that occur in other system types (for example, calc-alkaline porphyry-epithermal and metasomatic iron (oxide) alkali-calcic). Importantly, as CMMI investigations and outcomes continue, the approaches developed can guide ongoing prospectivity and assessments of the critical mineral resource potential in the partner countries.

Mineral resource assessments

The Energy Act of 2020 (Division Z of the Consolidated Appropriations Act of 2021) directs the USGS to accelerate national-scale resource assessments of all minerals on the whole-of-government list of critical minerals. Since the passage of the Energy Act, the USGS has launched initial regional critical mineral resource assessments in addition to partnering toward several methodological advances designed to accelerate the next assessments in the series. The mineral systems approach developed through the CMMI is accelerating the development of assessments by considering multiple minerals.

Figure 9

A map showing the distribution of tailings (blue circles) from the USMIN database (Horton and San Juan, 2016). The size of the blue circles is proportional to the areal footprint of the tailings features.



The new USGS regional assessments serve as the foundation for national assessments as new data and mapping become available through Earth MRI. In addition, the USGS is investing in both research, to update the deposit models that support assessments, and innovations in assessment methodologies. For example, current mineral resource assessment methodologies rely on human expertise and knowledge-driven workflows. Although these methodologies have proven effective, the increasing volumes of available data and the time required to process it present a significant barrier to rapidly conducting mineral resource assessments for the many deposit types that host critical mineral commodities.

The USGS partnered with the Defense Advanced Research Projects Agency (DARPA) to explore opportunities to make mineral resource assessment workflows more efficient and to fulfill its mission to map the distribution of critical mineral commodities (Lederer et al., 2023; DARPA, 2022). Compiling and preparing geoscientific information in a machine-readable and analysis-ready form consumes much of the time needed to conduct assessments. Whereas geochemical and geophysical data exist as structured or semistructured numerical datasets, most geologic maps and descriptive reports of mineralized areas remain in unstructured human-readable formats, thereby constraining their use in data-driven methodologies. This is especially true for nongeoreferenced maps held in historical collections which represent rich sources of input data that, if converted to digital form, could significantly aid in the prediction of the location of undiscovered deposits. Despite the usefulness of digital geologic maps, they are often not available at the requisite scales because it involves digitization of thousands of individual maps. Unlocking the information contained in text and images published in the predigital era could have a transformative impact on the ability to extract and integrate geoscientific information across disciplines.

With the goal of streamlining assessment workflows, a machine-learning competition was formulated that concentrated on two tasks related to processing geologic and mineral resource maps (Fig. 11). The first task focused on automatically identifying the location represented in a map and relating control points to geographic coordinates (that is, georeferencing). The second task utilized annotations in the map explanation or legend to automatically extract the corresponding points, lines and polygons that represent geological features such as mines, faults and lithologic units. Together, automation of these highly manual

Figure 10

Element concentration ranges (Se, Cu, Te, Mo and Re) for U.S. porphyry deposits where at least 10 samples are reported in the initial CMiO database. Total metric tons of ore from Hammarstrom et al. (2019) are also listed. These types of exploratory data can help with estimating tonnages of byproduct commodities relative to copper production. They can also guide research into why different deposits have disparate metal concentrations/ratios. For box plots: dot = average, central line = median).

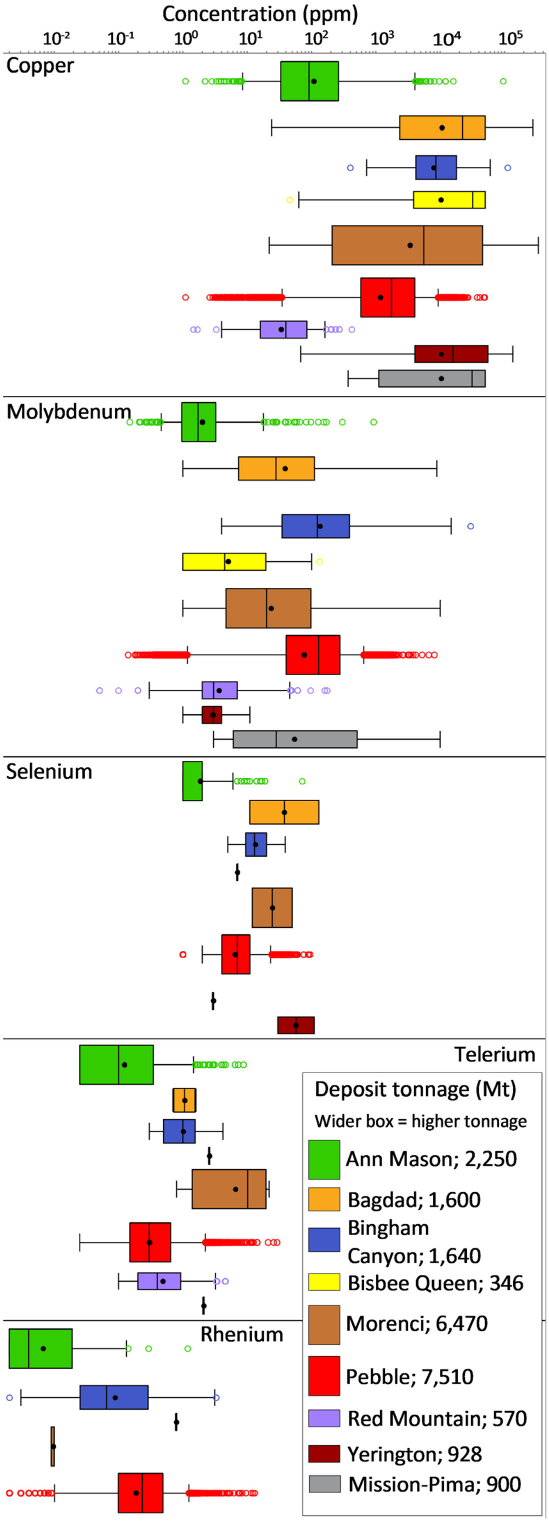
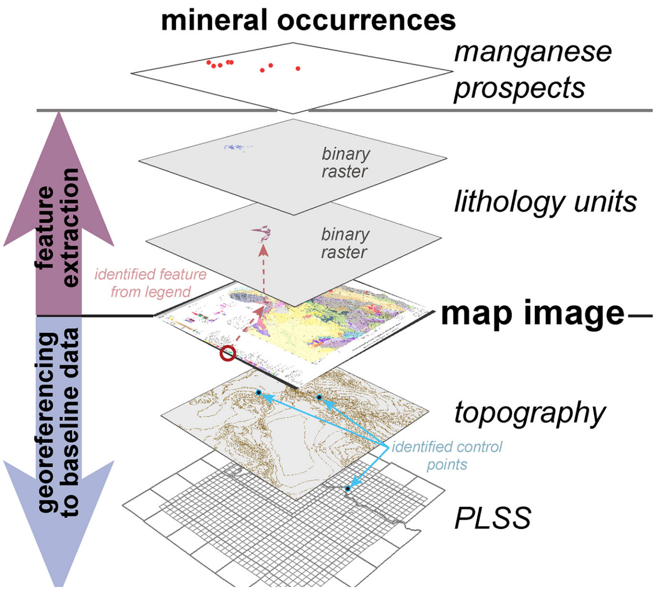


Figure 11

A diagram relating a map to the two DARPA challenges. (PLSS: Public Land Survey System) (Lederer et al., 2023; DARPA, 2022).



workflows can result in significant time and cost savings, prepare map data for use in geographical information systems in a format suitable to analysis, and effectively capture and preserve information currently locked in inaccessible formats.

Concluding remarks

As the United States moves past the lingering effects of the COVID-19 pandemic, the impacts on mineral commodity supply chains are visible in recent publications, particularly on domestic consumption (see Figs. 11 to 13 in USGS, 2023). While some commodities were not significantly impacted, others, including critical minerals such as rare earths and cobalt, saw large decreases in 2020, followed by large increases in 2021 and 2022. The consumption of most commodities now appears to be trending back to prepandemic levels. While the worst effects of the pandemic may be behind us, other large macroeconomic, and geopolitical factors exist. The global energy transition, an industrial revolution-scale transformation (Laurent, 2022), is picking up speed as renewables, energy storage and electric-vehicle adoption continue to accelerate. This transition has been accompanied by a growing recognition that the United States and other market economies may adopt technologies for which the mining and mineral processing stages of the supply chains are largely absent domestically (World Bank, 2017).

The invasion of Ukraine by Russia pressures mineral commodity supply chains (OECD, 2022) in at least two ways. Supply is constrained by economic sanctions on Russia, a major mineral commodity producer, which makes significant volumes of several mineral commodities off-limits to Western nations. Demand is simultaneously increased to supply the military consumption by Russia, Ukraine and supporting nations. In addition, China continues to dominate upstream critical mineral supply-chain nodes for important mineral commodities needed for semiconductors and other advanced technologies. These factors, and others, are likely to keep the security of critical mineral supply chains a highly visible challenge for U.S. policymakers for the foreseeable future. U.S. vulnerabilities to critical mineral supply chains resulting from import reliance, coupled with increasing concentration of production in countries which do not share the values of market economies is an ongoing challenge (Fortier et al., 2015, Nassar et al., 2020b). The USGS continues to play an important role in U.S. government efforts to address critical mineral concerns by providing fact-based, objective mineral information, mineral resource assessments, mapping and surveys, and basic research, in line with the Mineral Resources Program mission. ■

References

Andersen, A.K., Hofstra, A.H., Nuelle, L.M., Schmidt, Pfaff, K., Kelly, N.M. (2020) Lithogeochemistry of the Hicks Dome Critical Mineral Resource, Illinois-Kentucky Fluorspar district, USA: Implications for Genesis, GSA annual meeting, October 25–28, Montreal, Canada, 1 p.

Andersen, A.K., Hofstra, A.H. and Nuelle, L.M. (2021) Hydrothermal HFSE (+HREE) mineralization in the Bear Lodge Alkaline Complex—A key to understanding the larger Hicks Dome critical mineral resource?: Goldschmidt Conference (virtual), July 4-9, Abstract 8190, 1p.

Bennett, M., Hofstra, A., Pribil, M., Andersen, A., Premo, W., McCafferty, A., Maria, A., Nuelle, L. (2022) Lead Isotope and Fluid Inclusion Investigations of the Hicks Dome Critical Mineral Resource, Illinois-Kentucky Fluorspar district, USA: Society of Economic Geologists Annual Meeting 2022, August 27-30, Denver CO.

Blengini, G.A., Latunussa, C.E.L., Eynard, U., Matos, C.T. de, Wittmer, D., Georgitzikis, K., Pavel, C., Carrara, S., Mancini, L., Unguru, M., Blagoeva, D., Mathieux, F., and Pennington, D. (2020) Study on the EU's list of critical raw materials - Final report: European Commission, Brussels.

Coyan, J. A., McCafferty, A. E., Graham, G. E., San Juan, C. A., Emsbo, P., Lawley, C.J.M., Gadd, M.G., Huston, D. L., Czarnota, K., Paradis, S., Peter, J., Hayward, N., Barlow, M. (2022) Knowledge-driven prospectivity modeling of clastic-dominated lead-zinc mineral systems for Australia, Canada, and the United States: Geological Society of America Abstracts with Programs. Vol 54, No. 5 doi: 10.1130/abs/2022AM-383248.

DARPA (2022) DARPA Critical Minerals Competition Uses AI to Accelerate Analytics, https://www.darpa.mil/news-events/2022-08-15 (accessed April 12, 2023).

Denny, F.B., Nelson, W.J., Breeden, J.R. and Lillie, R.C. (2020) Mines in the Illinois portion of the Illinois-Kentucky Fluorspar District: Illinois State Geological Survey, Circular 604, 73 p. and 1:50,000-scale map.

Denny, F.B. and Kershaw, C.T. (2021) Bedrock geology of Hicks Dome, Hardin and Pope Counties, Illinois: Illinois

State Geological Survey, Illinois County Geologic Map, USGS-EMRI contract report, EMRI Hicks Dome-BG, 2 sheets, 1:12,000-scale; report, 145 p.

Department of Defense (2020) DOD Announces Rare Earth Element Awards to Strengthen Domestic Industrial Base, https://www.defense.gov/News/Releases/Release/Article/2418542/dod-announces-rare-earth-element-awards-to-strengthen-domestic-industrial-base/ (accessed March 21, 2023).

Department of Energy (2022) LPO Offers First Conditional Commitment for Critical Materials Project for Syrah Vidalia to Support Domestic EV Supply Chain https://www.energy.gov/lpo/articles/lpo-offers-first-conditional-commitment-critical-materials-project-syrah-vidalia (accesed March 21, 2023).

Dicken, C.L., Woodruff, L.G., Hammarstrom, J.M., and Crocker, K.E. (2022) GIS, supplemental data table, and references for focus areas of potential domestic resources of critical minerals and related commodities in the United States and Puerto Rico: U.S. Geological Survey Data Release, https://doi.org/10.5066/P9DIZ9N8.

Earth MRI (2023) Earth Mapping Resources Initiative (Earth MRI) | U.S. Geological Survey (usgs.gov) (accessed March 22, 2023).

Emsbo, P. (2009) Geologic criteria for the assessment of sedimentary exhalative (sedex) Zn-Pb-Ag deposits: U.S. Geological Survey Open-File Report 2009–1209, 21 p. https://pubs.usgs.gov/of/2009/1209/ (accessed March 23, 2023).

Emsbo, P., Lawley, C., and Czarnota, K. (2021) Geological surveys unite to improve critical mineral security: Eos, 102, https://doi.org/10.1029/2021EO154252.

Federal Register (2017) A Federal Strategy for Ensuring Secure and Reliable Supplies of Critical Minerals, Executive Order 13817, https://www.federalregister.gov/documents/2017/12/26/2017-27899/a-federal-strategy-to-ensure-secure-and-reliable-supplies-of-critical-minerals (accessed March 21, 2023).

Federal Register (2018) Final List of Critical Minerals 2018, https://www.federalregister.gov/documents/2018/05/18/2018-10667/final-list-of-critical-minerals-2018 (accessed March 21, 2023).

Federal Strategy (2019) A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals, U.S. Department of Commerce, https://www.commerce.gov/data-and-reports/reports/2019/06/federal-strategy-ensure-secure-and-reliable-supplies-critical-minerals (accessed March 21, 2023).

Fortier, S.M., DeYoung, J.H., Jr., Sangine, E. S., and Schnebele, E. K. (2015) Comparison of U.S. net import reliance for nonfuel mineral commodities—A 60-year retrospective (1954–1984–2014), https://doi.org/10.3133/fs20153082.

Fortier, S.M., Nassar, N.T., Lederer, G.W., Brainard, J., Gambogi, J., & McCullough, E.A. (2018). Draft critical mineral list—Summary of methodology and background information—U.S. Geological Survey technical input document in response to Secretarial Order No. 3359 https://doi.org/10.3133/ofr20181021.

Frenzel, M., Hirsch, T., and Gutzmer, J. (2016a) Gallium, germanium, indium, and other trace and minor elements in sphalerite as a function of deposit type — A meta-analysis: Ore Geology Reviews, v. 76, p. 52–78.

Frenzel, M., Ketris, M.P., Seifert, T., and Gutzmer, J. (2016b) On the current and future availability of gallium: Resources Policy, v. 47, p. 38–50.

Frenzel, M., Mikolajczak, C., Reuter, M.A., and Gutzmer, J. (2017) Quantifying the relative availability of high-tech by-product metals – The cases of gallium, germanium and indium: Resources Policy, v. 52, p. 327–335.

Geoscience Australia (2021) Critical Minerals Mapping Initiative http://criticalminerals.org/ (accessed February 8, 2023).

Granitto, M., Schmidt, D.E., Karl, N.A., and Khoury, R. M. (2021) National Geochemical Database on Ore Deposits: Legacy data: U.S. Geological Survey data release, https://doi.org/10.5066/P944U7S5.

Hammarstrom, J.M., Zientek, M.L., Parks, H.L., Dicken, C.L., and the U.S. Geological Survey Global Copper Mineral Resource Assessment Team (2019) Assessment of undiscovered copper resources of the world, 2015 (ver. 1.2, December 2021): U.S. Geological Survey Scientific Investigations Report, https://doi.org/10.3133/sir20185160.

Hammarstrom, J.M., Kreiner, D., Dicken, C.L, and Woodruff, L.G. (2023) National map of focus areas for potential critical mineral resources in the United States: U.S. Geological Survey Fact Sheet 2023–3007, 4 p., https://doi.org/10.3133/fs20233007.

Hayes, S.M., and Ramos, N.A. (2019) Surficial geochemistry and bioaccessibility of tellurium in semiarid mine tailings: Environmental Chemistry, v. 16, no. 4, p. 251.

Hayes, S.M., McAleer, R.J., Piatak, N.M., White, S.J.O., and Seal, R.R., II (2023) A novel non-destructive workflow for examining germanium and co-substituents in ZnS: Frontiers in Earth Science, v. 11, article 939700.

Hofstra, A., Lisitsin, V., Corriveau, L., Paradis, S., Peter, J., Lauzière, K., Lawley, C., Gadd, M., Pilote, J., Honsberger, I., Bastrakov, E., Champion, D., Czarnota, K., Doublier, M., Huston, D., Raymond, O., VanDerWielen, S., Emsbo, P., Granitto, M., and Kreiner, D. (2021) Deposit classification scheme for the Critical Minerals Mapping Initiative Global Geochemical Database: U.S. Geological Survey Open-File Report 2021–1049, 60 p., https://doi.org/ 10.3133/ ofr20211049.

Horton, J.D., and San Juan, C.A. (2016) Prospect- and mine-related features from U.S. Geological Survey 7.5- and 15-minute topographic quadrangle maps of the United States (ver. 9.0, January 2023): U.S. Geological Survey Data Release, https://doi.org/10.5066/F78W3CHG.

Huston, D.L., Champion, D.C., Czarnota, K., Duan, J., Hutchens, M., Paradis, S., Hoggard, M., Ware, B., Gibson, G.M., Doublier, M.P., Kelley, K.D., McCafferty, A., Hayward, N., Richards, F., Tessalina, S., Carr, G. (2022) Zinc on the edge—isotopic and geophysical evidence that cratonic edges control world-class shale-hosted zinc-lead deposits: Mineralium Deposita, https://doi.org/10.1007/s00126-022-01153-9.

Jenkins, J.A., Musgrove, M., and White, S.J.O. White (2023) Outlining potential biomarkers of exposure and effect to critical minerals: nutritionally essential trace elements and the rare earth elements: Toxics, v. 11, article 188.

Josephson, A.E. (2016) The behavior of tellurium during copper ore processing at the American Smelting and Refining Company (Tucson, AZ), https://www.semanticscholar.org/paper/The-behavior-of-tellurium-during-copper-ore-at-the-Josephson/fbb4faed5fed7f89bf2317b0e3119a2ce96345c6 (accessed March 23, 2023).

Kelley, K.D. (2020) International geoscience collaboration to support critical mineral discovery: U.S. Geological Survey Fact Sheet 2020–3035, 2 p., https://doi. org/10.3133/fs20203035.

Kelley, K.D., Huston, D.L., and Peter, J.M. (2021) Toward an effective global green economy: The Critical Minerals Mapping Initative (CMMI): SGA News, No. 48, March 2021, p. 1–5. https://e-sga.org/fileadmin/sga/ newsletter/news48/SGANews48_low.pdf, accessed March 22, 2022.

Laurent, T. (2022) The Fourth Industrial Revolution and the Energy Trilemma: Power https://www.powermag.com/the-fourth-industrial-revolution-and-the-energy-trilemma/ (accessed March 27, 2023).

Lawley, C.J.M., McCafferty, A.E., Graham, G.E., Huston, D.L., Kelley, K.D., Czarnota, K., Paradis, S., Peter, J.M., Hayward, N., Barlow, M., Emsbo, P., Coyan, J., San Juan, C.A., and Gadd, M.G. (2022) Data-driven prospectivity modelling of sediment-hosted Zn-Pb mineral systems and their critical raw materials: Ore Geology Reviews, v. 141, https://doi.org/10.1016/j.oregeorev.2021.104635.

Lederer, G.L., Rosera, J.M., and Goldman, M. (2023) Automated solutions for georeferencing and vectorizing geological maps [abs.]: Geological Society of America Abstracts with Programs, v. 55, https://www.geosociety.org/GSA/Publications/Meeting_Abstracts/GSA/Events/Abstracts.aspx?hkey=e6d15b07-b96d-4ec3-986a-c4c9d8e2c10c (accessed April 12, 2023).

Licht, C., Peiró, L.T., and Villalba, G. (2015) Global substance flow analysis of gallium, germanium, and indium: Quantification of extraction, uses, and dissipative losses within their anthropogenic cycles: Journal of Industrial Ecology, v. 19, no. 5, p. 890–903.

Lukoczki, G., Dietsch, C., Hickman, J.B., Morris, E., Curl, D.C., Pulliam, C., Vicroy, S. and Andrews, W.M. Jr., (2022) Phase I Activities of the Earth Mapping Resources Initiative (Earth MRI) in the Western Kentucky Fluorspar District: Kentucky Geological Survey Report of Investigations 66.

Lusty, P.A.J., Shaw, R.A., Gunn, A.G., and Idoine, N.E. (2022) UK criticality assessment of technology critical minerals and metals, https://www.bgs.ac.uk/download/uk-criticality-assessment-of-technology-critical-minerals-and-metals/ (accessed March 21, 2023).

Manley, R.L., Alonso, E., Nassar, N.T. (2022a) A model to assess industry vulnerability to disruptions in mineral commodity supplies: Resources Policy, https://doi.org/10.1016/j.resourpol.2022.102889.

Manley, R.L., Alonso, E., Nassar N.T. (2022b) Examining industry vulnerability: A focus on mineral commodities used in the automotive and electronics industries: Resources Policy https://doi.org/10.1016/j.resourpol.2022.102894.

McCafferty, A.E. (2016a) Helicopter magnetic and gravity gradiometry survey over the Pea Ridge iron mine and surrounding area, southeast Missouri, 2014: U.S. Geological Survey Data Release, https://doi.org/10.5066/F78P5XM4.

McCafferty, A.E. (2016b) Airborne magnetic and radiometric survey, Ironton, Missouri area: U.S. Geological Survey Data Release, https://doi.org/10.5066/F7B56GT8.

McCafferty, A.E. (2022) Geophysical activities related to critical mineral mapping in the southern Midcontinent, USA: Geological Society of America Annual Meeting, Denver, Colorado. https://doi.org/10.1130/abs/2022AM-376891.

McCafferty, A.E., Phillips, J.D., and Driscoll, R.L. (2016) Magnetic and gravity gradiometry framework for Mesoproterozoic iron oxide-apatite and iron oxide-copper-gold deposits, southeast Missouri: Economic Geology, v. 111, pp. 1859-1882.

McCafferty, A.E., Phillips, J.D., Hofstra, A.H., and Day, W.C. (2019) Crustal architecture beneath the southern Midcontinent (USA) and controls on Mesoproterozoic iron oxide-apatite and iron oxide-copper-gold mineralization from 3D geophysical models: Ore Geology Reviews, v. 111, pp. 102966.

McCafferty, A.E., and Johnson, M.R. (2019) Airborne magnetic and radiometric survey, southeast Missouri and western Illinois, 2018-2019: U.S. Geological Survey data release, https://doi.org/10.5066/P9PBDSA1.

McCafferty, A.E., and Brown, P.J. (2020) Airborne magnetic and radiometric survey, southeastern Illinois, western Kentucky, and southern Indiana, 2019: U.S. Geological Survey Data Release, https://doi.org/10.5066/P9R05B0M.

McCafferty, A.E., and Connell, D.M. (2022) Airborne horizontal-magnetic gradient and radiometric survey over parts of southeast Missouri, southern Illinois and western Kentucky - The Gap survey, 2021: U.S. Geological Survey Data Release, https://doi.org/10.5066/P9TK8KMM.

McCullough, E. and Nassar, N.T. (2017) Assessment of critical minerals: updated application of an early-warning screening methodology: Miner Econ 30, 257–272 (2017). https://doi.org/10.1007/s13563-017-0119-6 (accessed March 21, 2023).

Moats, M., Alagha, L., and Awuah-Offei, K. (2021) Towards resilient and sustainable supply of critical elements from the copper supply chain: A review: Journal of Cleaner Production, v. 307, p. 127207.

Nassar, N.T., Brainard, J., Gulley, A., Manley, R., Matos, G., Lederer, G., Bird, L.R., Pineault, D., Alonso, E., Gambogi, J., and Fortier, S.M. (2020a), Evaluating the mineral commodity supply risk of the U.S. Manufacturing sector: Science Advances, v. 6, no. 8.

Nassar, N.T., Alonso, E., and Brainard, J. (2020b) Investigation of U.S. Foreign Reliance on Critical Minerals—U.S. Geological Survey Technical Input Document in Response to Executive Order No. 13953 Signed September 30: U.S. Geological Survey Open-File Report 2020–1127, accessed at https://pubs.er.usgs.gov/publication/ofr20201127.

Nassar, N.T., and Fortier, S.M. (2021) Methodology and technical input for the 2021 review and revision of the U.S. Critical Minerals List: https://doi.org/10.3133/ofr20211045.

Nassar, N.T., Graedel, T.E., and Harper, E.M. (2015) By-product metals are technologically essential but have problematic supply: Science Advances, v. 1, no. 3, p. e1400180.

Nassar, N.T., Kim, H., Frenzel, M., Moats, M., and Hayes, S. (2022) Global tellurium supply potential from electrolytic copper refining: Resources, Conservation and Recycling, p. in review.

National Research Council (2008) Minerals, Critical Minerals, and the U.S. Economy. Washington, DC: The National Academies Press. https://doi.org/10.17226/12034.

National Science and Technology Council (2016) Assessment of Critical Minerals: Screening Methodology and Initial Application, Office of Science and Technology Policy, Executive Office of the President, https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/NSTC/csmsc_assessment_of_critical_minerals_report_2016-03-16_final.pdf (accessed March 21, 2023)

New York Times (2010) Amid Tension, China Blocks Vital Exports to Japan, https://www.nytimes.com/2010/09/23/business/global/23rare.html (accessed March 28, 2023).

Ojebuoboh, F. (2008) Selenium and tellurium from copper refinery slimes and their changing applications: World of Metallurgy–Erzmetall, v. 61, no. 1, p. 33–39.

OECD (2022) The supply of critical raw materials endangered by Russia's war on Ukraine https://www.oecd.org/ukraine-hub/policy-responses/the-supply-of-critical-raw-materials-endangered-by-russia-s-war-on-ukraine-e01ac7be/ (accessed March 27, 2023).

U.S. Geological Survey (2021) Historical statistics for mineral and material commodities in the United States, at https://www.usgs.gov/centers/national-minerals-information-center/historical-statistics-mineral-and-material-commodities.

U.S. Geological Survey (2022) Geochemical data generated by projects funded by the USGS Earth Mapping Resources Initiative (ver. 7.0, November 2022): U.S. Geological Survey Data Release, https://doi.org/10.5066/P9WHRLXH.

U.S. Geological Survey (2023) Mineral Commodity Summaries 2023, https://doi.org/10.3133/mcs2023.

USTR (2023) Office of the United States Trade Representative: Free Trade Agreements, https://ustr.gov/trade-agreements/free-trade-agreements (accessed March 21, 2023).

White, S.J.O., Piatak, N.M., McAleer, R.J., Hays, S.M., Seal, R.R., II, Schaider, L.A., and Shine, J.P. (2022) Germanium redistribution during weathering of Zn mine wastes: implications for environmental mobility and recovery of acritical mineral: Applied Geochemistry, v. 143, article 105341.

World Bank (2017) https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf (accessed March 28, 2023).