

USGS critical minerals review

by **Graham Lederer, Jamey Jones, Darcy McPhee, Jeff Mauk, Robert Seal, Kate Campbell, Jane Hammarstrom, Paul Bedrosian, Patricia MacQueen, Garth Graham, Federico Solano, George Case and David Pineault, U.S. Geological Survey**

As the science agency for the Department of the Interior, the U.S. Geological Survey (USGS) provides scientific information to support policy decisions on the stewardship of natural resources essential for economic and national security. Recent legislation reaffirms the original mission of the USGS articulated in the Organic Act of 1879 (43 U.S.C. 31) as “the classification of the public lands and examination of the geological structure, mineral resources, and products of the national domain” and focuses research and assessment efforts on critical minerals.

The 2022 Final List of Critical Minerals includes 50 critical minerals (U.S. Geological Survey, 2022a) supported by a published methodology (Nassar and Fortier, 2021; Nassar et al., 2020). Because supply risk reflects market dynamics and evolving mineral commodity supply chains, monitoring of commodity statistics (U.S. Geological Survey, 2024a) is essential for maintaining a robust critical minerals list and methodology. Pursuant to the Energy Act of 2020 (30 U.S.C. 1606), a draft list is prepared, revised, finalized and published in the Federal Register on a three-year cycle.

The Infrastructure Investment and Jobs Act (43 U.S.C. 311), also known as the Bipartisan Infrastructure Law, directed the USGS Earth Mapping Resources Initiative (Earth MRI) to complete an initial comprehensive national modern surface and subsurface mapping and data integration effort. The initiative emphasizes the recoverable critical minerals in surface or subsurface deposits and prioritizes mapping and critical mineral assessments. Earth MRI activities reinforce the goals of the USGS Energy and Mineral Resources Mission Area to conduct research and assessments that focus on the location, quantity and quality of mineral and energy resources, including the economic and environmental effects of resource extraction and use.

This article reviews the ongoing research activities on critical minerals conducted by the USGS Mineral Resources Program in 2023. Contributions range from (1) Earth MRI activities on data acquisition, mine wastes and geochemical characterization, (2) critical mineral investigations in the United States, (3) international collaboration and (4) a better understanding of the supply chains of byproduct critical minerals. Although it is impractical

to highlight all the important work carried by USGS staff and scientists, these selected contributions convey the depth and breadth of research activity on critical mineral priorities and partnerships.

Earth Mapping Resources Initiative (MRI)

In 2019, Congress provided funds to the USGS for a new initiative, Earth MRI, to cover the nation with an optimal mix of high-resolution geoscience data and derivative map types and interpretations required to address future needs for critical mineral resources, as well as other national, regional or local needs. Earth MRI was established as a long-term, multiyear effort to support our nation’s understanding of its subsurface geology and critical mineral resources by acquiring and interpreting new high-resolution 3D geophysical, geologic and topographic (elevation) data across the nation. In 2021, supplemental funding through the Infrastructure Investment and Jobs Act (43 U.S.C. 311) significantly accelerated collection of these fundamental geologic datasets, broadened Earth MRI’s scope to include evaluation of potential aboveground resources and mine waste, and provided new opportunities for data integration and analysis. Earth MRI was established initially as a partnership between the USGS and state geological surveys. The close cooperation between federal and state geologists has been a hallmark of this initiative and key to its accomplishments. In the five years since its inception, Earth MRI has established relationships with additional federal, state and industry partners that may be leveraged to build new partnerships and develop new products to increase the nation’s knowledge of its subsurface and aboveground geology, topography and potential critical mineral resources.

To guide Earth MRI data collection efforts across the nation, the USGS delineated focus areas for 23 mineral systems throughout the United States that could potentially host mineral deposits enriched in critical minerals (Dicken et al., 2022). These focus areas were developed in partnership with state geological surveys, and provide an initial, broad screening tool for targeting areas for new data acquisition. A mineral systems framework encompasses all the deposit types and the various mineral commodities that are known or suspected

to occur within the system, and it highlights all possible critical mineral associations for each system whether they occur as a primary commodity or as a potential coproduct or byproduct (Hofstra and Kreiner, 2020; Hofstra et al., 2021). The USGS also developed a new database that identifies individual mineral deposits that have documented critical mineral associations, which includes published information about the size and status of each entry (Hammarstrom et al., 2023). In the database, individual deposits are given a ranked value determined from their critical mineral status (that is, past, current or potential future producers) and the presence or absence of known reserves or resources. Among 681 known deposits contained in the database, more than 200 entries are identified as having documented critical minerals but no evidence of present or past production, thus representing potential for untapped critical mineral resources in the nation. This mineral deposit database was designed to be used in conjunction with the focus area map and associated geospatial database (Dicken et al., 2022) to better understand critical mineral occurrences and their distribution within host mineral systems and mineral deposits, and to identify the most prospective geologic settings and regions for new data collection through Earth MRI.

The early emphasis of Earth MRI data collection was on updating geophysical, geologic and topographic (elevation) datasets across the nation. Since its inception, Earth MRI has funded 12 new lidar surveys through the USGS 3D Elevation Program (3DEP), contributing new high-resolution topographic data that cover more than 700,000 km² of the United States. To date, 80 geologic and geochemical mapping projects have been funded across 32 different states to better understand connections between the bedrock geologic framework and contained mineral resources in each area. Some projects involve detailed geologic mapping, whereas others involve systematic sampling for modern geochemical data and span multiple states. Earth MRI has acquired 24 airborne magnetic and radiometric surveys, more than doubling the amount of high-quality magnetic data for the conterminous United States and covered the entire island of Puerto Rico. Earth MRI also funded five airborne magnetic surveys in Alaska published by the Alaska Division of Geological and Geophysical Surveys, more than quadrupling the amount of previously available high-quality magnetic data. Airborne magnetic and radiometric surveys are essential for mapping and modeling the bedrock geologic

framework in regions that have limited bedrock exposure or younger sedimentary cover. In some instances, airborne magnetic and radiometric data can be used to directly identify and map mineralized areas (for example, Shah et al., 2021; Wang et al., 2023). The Earth MRI Acquisitions Viewer (<https://ngmdb.usgs.gov/emri/#3/40/-96>) is a regularly updated web portal that provides information on data collection activities, project status, brief project descriptions, points of contact, and links to data for completed projects.

In 2023, Earth MRI funded nine high-quality airborne magnetic and radiometric surveys that will cover more than 300,000 km² of the United States. Two additional surveys designed and contracted by Earth MRI staff were supported by Federal Disaster Supplemental Funding (Florida) or state funding (Wyoming). Planned surveys in the eastern part of the United States focus on a variety of mineral systems in the Adirondack lowland regions of northwestern New York, on Piedmont crystalline rocks and on Atlantic Coastal Plain sediments in North Carolina and surrounding states. The North Carolina survey expands prior work in the region (for example, Shah et al., 2021), extending coverage across the Fall Line into bedrock terranes of the southeastern Appalachian Mountains. The magnetic and radiometric survey planned for northern and central Florida can support geologic mapping and research for industrial and critical minerals over areas hosting phosphates, heavy mineral sands and mine waste. In the central United States, a large magnetic and radiometric survey is ongoing for the Cuyuna Iron Range of northcentral Minnesota, targeting iron-bearing strata with unusually high concentrations of manganese. The survey outline also encompasses other mineral systems that include known magmatic sulfide deposits. Another regional survey covering western Kentucky, northwestern Tennessee and parts of surrounding states targets a large buried magnetic anomaly and is designed to meet complementary needs related to geologic mapping, earthquake hazards and mineral resource research. This area includes well-known lead-zinc mining districts that have potential for additional critical mineral resources. When completed, the Kentucky-Tennessee survey can be merged with other Earth MRI magnetic and radiometric surveys to provide complete, high-quality coverage over an area extending from eastern Kentucky to southern Arkansas. This expanded coverage can be used to map mineral systems and model deeper crustal boundaries inferred to control overlying system geometries and possibly

influence fluid flow and mineralization at a variety of scales (McCafferty et al., 2023a).

Five different magnetic and radiometric surveys were funded in 2023 in the western United States. In the Southwest, a large survey was designed over a portion of the porphyry copper belt in southeastern Arizona. The Arizona survey extends a 2022 survey of the New Mexico portion of the porphyry belt and the two can be merged to provide continuous coverage across the state boundary. The new high-resolution survey data can help define potential concealed mineral resources under extensive Cenozoic basin fill and complement ongoing mapping and geochemical studies underway by the USGS and the Arizona Geological Survey. A new survey in southwestern Utah is focused on important mineral-rich regions, including the Goldstrike, Iron Axis and Tutsagubet mining districts. These districts contain critical minerals such as antimony, barite, gallium and germanium, in addition to other important minerals such as copper, gold, iron, phosphorus, selenium and silver. Data from the Utah Iron Axis survey can help identify bedrock features in large areas under cover and help map the geology of the shallow subsurface. When this survey is merged with a similar survey funded in 2022, high-resolution magnetic and radiometric data will extend across western Utah from Provo to the Arizona border. In Colorado, a new magnetic and radiometric survey will cover the middle and southwestern portions of the Colorado Mineral Belt. The new survey overlaps with an active Earth MRI geologic mapping project being conducted by the Colorado Geological Survey in the La Plata mining district, where mapping and geophysical data can provide new insights into mineralizing events in the region. In central Wyoming, the Wyoming State Geological Survey contributed funding for a magnetic and radiometric survey extending from the southern Wind River Mountains east to the Granite Mountains (U.S. Geological Survey, 2024b). The survey is focused on the areas encompassing the Oregon Trail Structural Belt, which might represent a suture between Precambrian terranes. This is an area with a rich history of past and current mineral exploration with known and suspected mineral systems of high interest for their critical mineral potential. In the northwestern United States, two new surveys were funded in eastern Idaho and western Montana. The Montana survey extends coverage from a 2022 survey to the west, encompassing the Boulder Batholith and the Butte, Philipsburg and Hecla mining districts. Combining the data

with geologic mapping and sampling by the Montana Bureau of Mines and Geology can help to develop an improved understanding of the geologic framework and mineral systems that underpin these well-known mining districts, which can aid assessment of and exploration for associated critical mineral commodities. In Idaho and westernmost Montana, a new survey is focusing on a large area of the Idaho Cobalt Belt and the western edge of the Montana-Idaho porphyry belt. These areas have the potential to host cobalt, titanium, niobium and rare earth elements (REEs), and the new airborne survey data can aid active geologic mapping projects by the Montana Bureau of Mines and Geology and Idaho Geological Survey.

In Alaska, Earth MRI funding in 2023 was used to continue airborne magnetic and radiometric data collection in the Kuskokwim Mountains region of the state. The second phase of the Kuskokwim Mountains survey, designed to Rank 2 specifications (Drenth and Grauch, 2019), covers more than 35,000 km². The Kuskokwim region of interior Alaska contains multiple overlapping mineral systems and numerous gold deposits that are the focus of active placer mining and regional mineral exploration. The region also contains known tin, REE, tungsten and antimony deposits and has high potential for additional undiscovered critical mineral deposits.

In addition to the new airborne magnetic and radiometric surveys outlined above, Earth MRI funded 14 new geologic and geochemical mapping projects that are being conducted by 18 different state geological surveys. Geologic mapping projects address topics such as Mississippi-Valley-type mineral deposits in Arkansas and Wisconsin, lithium-bearing strata in southeastern California, and copper and cobalt deposits in central Maryland. Reconnaissance geochemical mapping projects, many of which involve multiple states, are addressing large regional systems such as metalliferous black shales in the eastern and central United States and REEs in granitic regolith in the Southeast. Multiple western states are partnering with USGS to modernize legacy geochemical data for samples collected by the National Uranium Resource Evaluation (NURE) program in the late 1970s and early 1980s. The NURE samples are archived at the USGS campus in Denver, CO, and geochemical reanalysis using advanced methods can provide new and important information about the concentration of critical elements in these archived materials.

Beginning in 2022, Earth MRI was able to

expand its scope of data collection activities to include airborne electromagnetic surveys, regional and district-scale hyperspectral remote sensing studies, and new projects focused on aboveground resources in mine waste. Four different airborne electromagnetic (AEM) surveys were conducted through 2023 in three regions of the United States. Electromagnetic surveys in eastern Alabama and western Alaska are focused on graphite-bearing mineral systems. Two AEM surveys in the Great Basin of western Nevada cover areas containing multiple mineral systems but are focused on those that have known or suspected potential to host lithium resources.

The USGS and NASA have partnered to generate modern hyperspectral surveys over 1.3 million km² in the semi-arid regions of the southwestern United States. Data are being acquired using NASA's Airborne Visible InfraRed Imaging Spectrometer (AVIRIS) sensors. The project will produce visible- to short-wavelength infrared (VSWIR) mineral maps of soils and exposed rocks that can provide new information on the location and formation of mineral systems with related hydrothermal alteration and rock-weathering processes. Additional data are being acquired using one of several thermal infrared (TIR) sensors, which support discrimination, identification and mapping of primary rock-forming minerals across the region. More targeted, district-scale hyperspectral surveys were funded over multiple areas in Florida to aid mapping in areas that are actively mined for phosphate-bearing rocks and gypsum. Another hyperspectral survey in Florida is being planned and contracted by Earth MRI staff using Federal Disaster Supplemental Funding, and the data and derived mineral maps are expected to provide actionable information about the location and distribution of critical and industrial minerals that can be used to produce fertilizer and aid in construction efforts related to hurricane recovery and resiliency. The data can also aid in geologic mapping and mine waste sampling work conducted by the Florida Geological Survey and funded by Earth MRI.

Finally, Earth MRI has also contributed consistently to the preservation of legacy data related to critical minerals through the USGS National Geological and Geophysical Data Preservation Program (NGGDPP). Support from Earth MRI through NGGDPP sponsors a variety of activities that can include development of strategic plans for addressing critical mineral resources in each state, legacy data collection and curation related to state mineral deposits or districts, rescue of

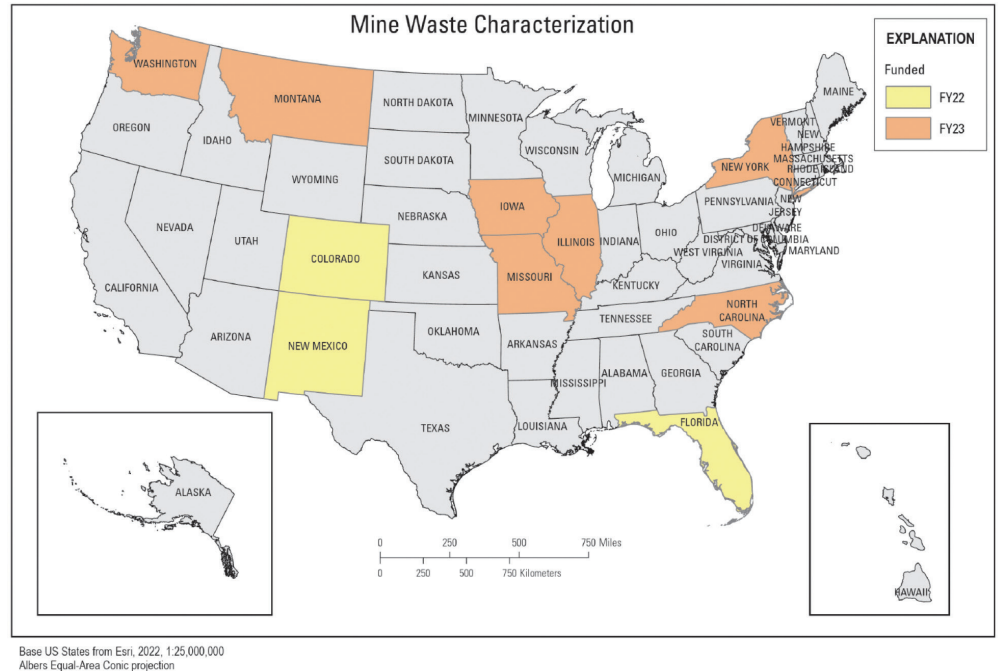
abandoned drill core and preservation and potential geochemical reanalysis of legacy rock samples and drill core. In 2023, 32 state geological surveys were supported by NGGDPP, enabling them to preserve vital geologic and geophysical data and samples. Results of these projects are made publicly available through multiple sites that may include published reports by state geological surveys, the USGS National Index of Borehole Information (NIBI, <https://webapps.usgs.gov/nibi/>), and the USGS Registry of Scientific Collections (ReSciColl, <https://webapps.usgs.gov/rescoll/index.html>).

Mine waste inventory. North and South America have long histories of mining, extending from well before European settlement to the present. For metallic mineral deposits, the concentrations of precious metals are typically measured in grams per metric ton, whereas base metals such as copper, lead and zinc typically come from orebodies with only a few percent, or less, of the commodity of interest. Most metallic mineral deposits have mine waste piles that are approximately equivalent to the total tonnage of processed material. Changes in mining technology, mineral processing, extractive metallurgy and mineral economics through time have enabled the recovery of metals with progressively lower grades, so that material that was low grade or waste in the past might now be economic to recover. In addition, more than half of the commodities on the United States' critical minerals list could be recovered as byproducts that contribute little to the overall revenue of mining operations (Nassar and Fortier, 2021). Many of these byproduct critical elements were not sought or recovered in the past, but developments in modern technology throughout the economy have increased the demand for commodities such as gallium, germanium, indium, rhenium, tellurium and other commodities. Therefore, some mine waste features may contain critical minerals or other commodities that could be recovered from reprocessing to help address the national need. Furthermore, reprocessing mine waste might remove or decrease the concentration of minerals that weather to form acid mine drainage or release toxic metals to the environment. For waste features that need remediation, reprocessing waste material could be a win-win situation, with revenue from commodities helping to offset the costs of remediation.

The Infrastructure Investment and Jobs Act of 2021 directed the USGS Earth MRI to collect data for areas containing mine waste

Figure 1

Map of the United States showing the funded Earth MRI mine waste characterization projects in fiscal years 2022 (FY22) and 2023 (FY23).



to increase understanding of aboveground critical mineral resources in previously disturbed areas. The USGS' Mineral Deposit Database project (USMIN) is collaborating with state geological surveys to build a comprehensive and authoritative inventory of nonfuel mine waste for the United States. In 2022, USMIN collaborated with state, federal and tribal agencies to develop the structure of the database that hosts mine waste records. The intent was to incorporate essential fields that would summarize the important characteristics of individual mine waste attributes, such as average geochemical grades of waste features, but not to provide details — such as geochemical analyses of multiple samples — that can be linked to from other databases. The database has two feature classes: points and polygons, and three tables: geology, resources and references. The points feature class provides the location of the mine waste feature, the name of the mine and mining district, and the surface management agency of the land where the feature occurs. This is a general field that is populated with first-order information, such as Bureau of Land Management, state or private. The polygon feature class captures the areal extent of each mine waste feature, and the database is meant to only capture features that are larger than 2,000 m². The geology table provides information for each feature about commodities, deposit type, mineral system, ore minerals and gangue minerals. The resources table has fields for reported volume, calculated volume, tonnage factor, grade and contained amount of each commodity. Populated records must use data that are available in the public domain, but not necessarily peer-reviewed, and the completed database must provide citations and references for these data. Each feature class and table have a citation field that indicates the source of the compiled data, and the references table provides the full reference for each citation.

In 2023, the USGS released a Notice of Funding Opportunity to fund state geological surveys to populate the mine waste database (U.S. Geological Survey, 2023b). Thirteen

states were funded to undertake this work, and USMIN personnel have completed training at 11 of those agencies, where work is currently progressing. The vision is that state geological surveys will help build the database by completing records for their states, and USMIN personnel will populate records for additional areas to help complete this national database.

Mine waste characterization. Earth MRI is funding state geological surveys to (1) conduct mine waste characterization studies at sites that may have potential for critical minerals and (2) assist in the development of a national database of abandoned mine sites. 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, seven additional states received funding for mine waste characterization studies: Illinois, Iowa, Missouri, New York, North Carolina, Montana and Washington (Fig. 1).

Collectively, the studies funded in 2022 and 2023 are investigating mine waste from more than 11 mineral deposit types that could contain more than 41 critical mineral commodities (Table 1). The 2024 proposal process is currently underway to fund additional states to conduct mine waste characterization studies to assess critical mineral potential.

Table 1

Selected mineral deposit types being investigated by the Earth MRI mine waste characterization program. (Critical mineral potentials based on Hofstra and Kreiner, 2020.)

Mineral deposit type	Potential critical mineral commodities
Arsenide veins	As, Bi, Co, F, Ni, REEs, Te, W, Zn
Iron oxide apatite (copper-gold)	Co, REEs
Low and intermediate sulfidation epithermal	As, Bi, Ga, Ge, In, Mn, Sb, Te, W
Mississippi Valley-type and sedimentary exhalative	Co, Ga, Ge, In, Sn, Zn
Pegmatite	Be, Cs, Li, Nb, Sc, Sn, Ta
Phosphorite	Cr, F, REEs
Porphyry copper	PGEs, Re, Sc, Te, Bi, Co

Critical mineral investigations in the United States

USGS research on critical minerals has continued on multiple fronts. Earth MRI adopted a mineral systems approach to outline broad areas of the United States that could host critical mineral deposits (Hofstra and Kreiner, 2020; Kreiner et al., 2023). Working with state geological surveys, the USGS developed a national map that shows the footprints of 23 different mineral systems that could host a variety of different mineral deposit types (Hammarstrom et al., 2023). Porphyry systems, for example, can include a range of related deposit types such as porphyry copper deposits, skarns, polymetallic veins, epithermal deposits and lithocaps, all of which can host critical minerals as principal commodities or as potential byproducts. More than 800 individual focus areas representing one or more mineral systems provide a basis for identifying areas where acquisition of new mapping, airborne geophysics and geochemical data are most needed to evaluate the critical mineral potential of the United States. Kreiner et al. (2023) summarized some of the early results of Earth MRI data acquisition efforts and showed how new data can be integrated using the mineral systems approach to develop mineral potential maps.

Historically, the United States produced all of the minerals included on the current critical minerals lists, albeit in some cases with wartime government subsidies and by small-scale mining operations (Kelly and Matos, 2014). In 2022, however, the United States was more than 50 percent import reliant for some 43 of the 50 individual critical mineral commodities (U.S. Geological Survey, 2023a). A new compilation of U.S. deposits that are known to contain critical

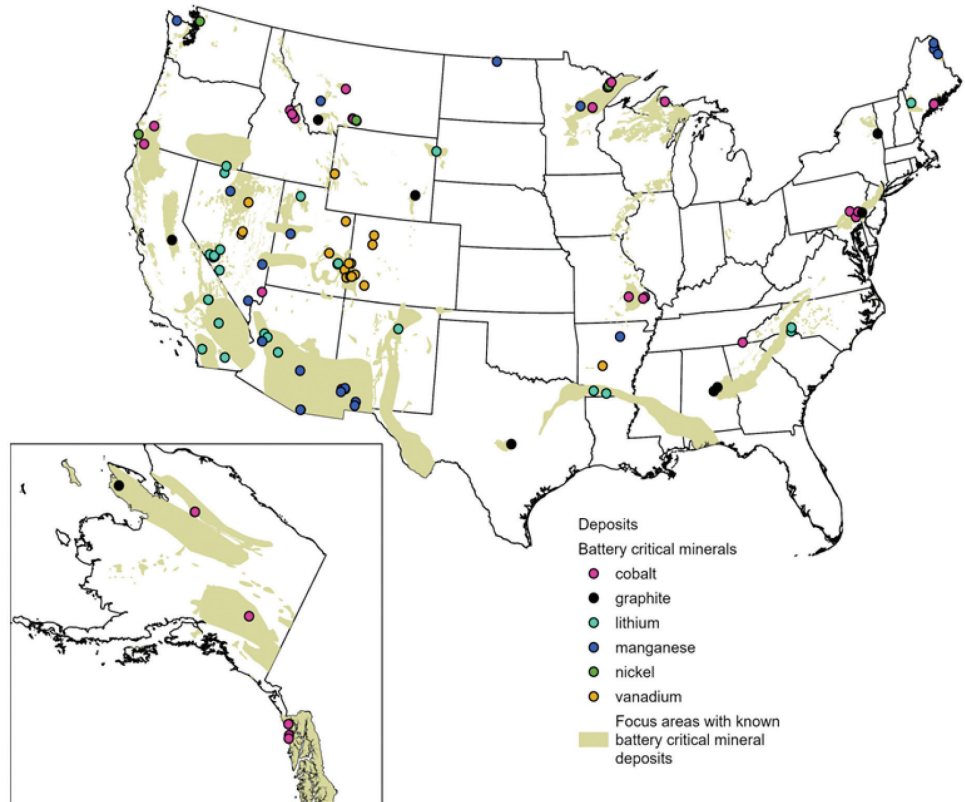
minerals from either past or current production data or from documented resource information includes more than 600 sites (Hammarstrom et al., 2023; Woodruff et al., 2023). Of these, only 28 deposits have reported critical mineral production since 2015 and not all of those 28 deposits were active in 2024. The geographic information system (GIS) and data tables include the mineral system, deposit type, and focus area for each deposit. Focus areas with known critical mineral deposits highlight areas of the country most likely to represent near-term domestic sources of critical minerals should development be possible. Areas of the country most likely to provide battery critical mineral resources, for example, include the Great Basin for lithium in brines and clays, the eastern United States for lithium in pegmatites, cobalt and nickel in mafic magmatic mineral systems in Minnesota and Michigan, cobalt from the iron oxide-copper-gold system in the Idaho Cobalt Belt, and the Seward Peninsula in Alaska for graphite (Fig. 2).

Noteworthy accomplishments over the past year include a comprehensive compilation of information about domestic deposits and resources of critical minerals in subduction-related hydrothermal systems (Vikre et al., 2023), petrochemical and geochronological studies in the vicinity of the Mountain Pass REE deposit in the Mojave Desert (California) to better understand the metallogeny of the region (Watts et al., 2024), and laboratory-based hyperspectral and satellite-based multispectral surveys of uranium deposits in Texas advanced the application of these techniques to both mine waste assessment and mineral exploration (Hubbard et al., 2023, 2024). In addition, the USGS continued its collaboration with state geological surveys to evaluate the critical mineral potential of mine waste through its Earth MRI mine waste characterization program.

Mineral systems that form in subduction-related tectonic terranes are significant producers of several important commodities such as copper, zinc, lead, gold and silver as well as other critical mineral commodities (Vikre et al., 2023). These mineral systems account for much of the mine production in the western United States and Alaska. Important mineral systems include the porphyry copper-molybdenum (Cu-Mo) system and porphyry deposits, several skarn and replacement deposit types, and epithermal deposits among others; the porphyry tin (Sn) system, which includes porphyry and skarn deposits; and several mineral deposit types that are unclassified

Figure 2

Map showing the distribution of a subset of focus areas that contain deposits with past production or identified resources of critical minerals used in electric-vehicle battery technologies. (Focus areas from Dicken et al., 2022; deposits from Hammarstrom et al., 2023).



relative to mineral systems, but are important sources of arsenic, antimony, beryllium, gallium, germanium, tungsten and fluorite (Vikre et al., 2023). Vikre et al. (2023) highlighted significant inventories of aluminum, antimony, potassium and tungsten in unmined deposits, equivalent to two to eight years of domestic consumption, and several decades of domestic consumption of arsenic, bismuth, fluorite, gallium, germanium and indium. They also noted that inventories of numerous critical minerals in porphyry Cu-Mo deposits, owing to their large size could supply domestic needs for periods ranging from decades to centuries on a commodity-by-commodity basis. However, they cautioned that these quantities should not be considered consumable supplies without formal definition of reserves and the development of viable mining plans and recovery strategies.

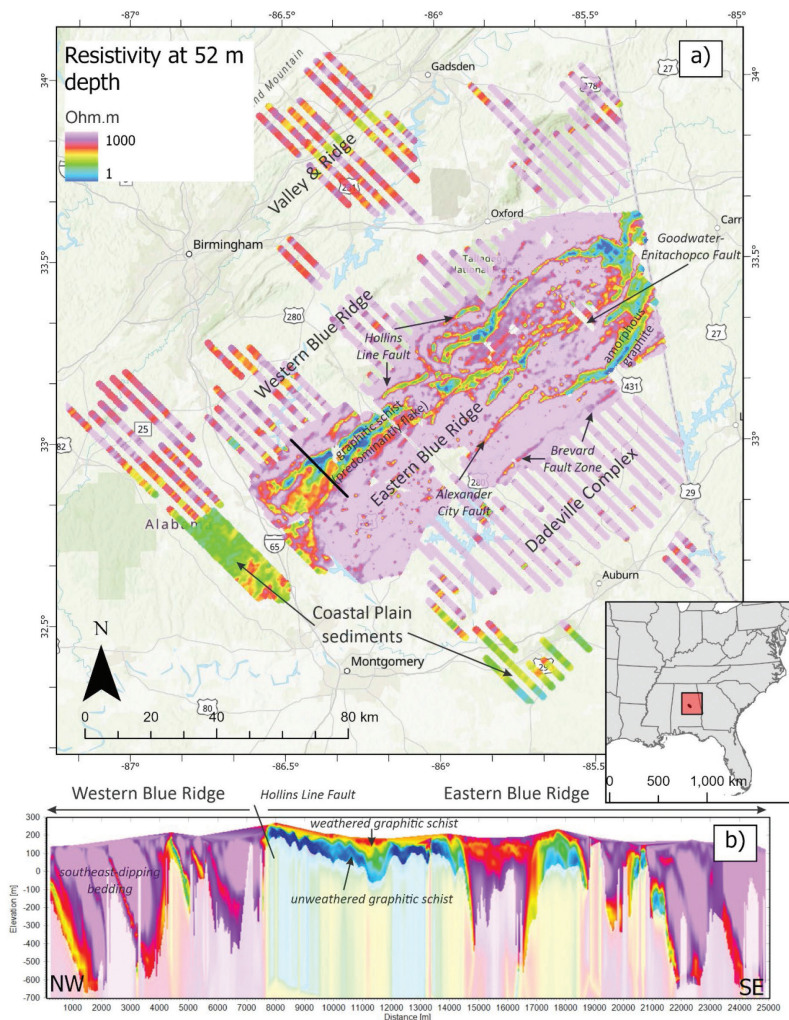
Watts et al. (2024) extended the scope of recent study of the geochemistry and geochronology of the magmatic rocks at the Mountain Pass REE deposit in the Mojave Desert, CA (Watts et al., 2022), to include the prospective Bobcat Hills region, 65 km southeast of Mountain Pass. Mountain Pass is the most economically significant REE deposit in the United States. Watts et al. (2022) were able to demonstrate spatial and temporal links between alkaline and carbonatitic intrusive activity at Mountain Pass. The Bobcat Hills REE-rich mafic alkaline magmatism is slightly older than magmatism at Mountain Pass. An important contrast between these two sites is that Bobcat Hills represents a single, short-lived intrusive event with limited crustal interaction, whereas Mountain Pass experienced multiple intrusive pulses that spanned tens of millions of years and included significant crustal assimilation. The authors suggested that the protracted intrusive history at Mountain Pass was a prerequisite for shallow emplacement of the carbonatite magmas that formed the ore.

The spectral reflectance signatures of sandstone-hosted uranium deposits and mine wastes in the Texas Coastal Plain were the subject of a satellite-based multispectral study (Hubbard et al., 2023; 2024). Uranium is not considered a nonfuel critical mineral; however, sandstone-hosted uranium deposits have historically been important sources of vanadium. Vanadium is a critical mineral that has been used extensively to strengthen steel and has growing importance in the emerging development of vanadium redox-flow batteries (Kelley et al., 2017). The laboratory-based hyperspectral study utilized spectra measured from archived rock cores, cuttings and other sample splits, which were then compared to mineral-specific spectral libraries. Collectively, these studies underscore the limitations of archived, satellite-based surveys, but highlight the promise of fixed-wing and new satellite-based hyperspectral sensors. Nevertheless, the results of these studies can aid mapping of waste materials from uranium mining and future exploration for sandstone-hosted deposits and their associated critical minerals.

In August 2023, the USGS in collaboration with the Defense Advanced Research Projects

Figure 3

(a) Depth slice through the resistivity models obtained from the 2023 Earth MRI survey of the Alabama Graphite-Vanadium Belt; colors correspond to resistivity at 52 m depth. Thick black line marks the location of the cross section. (b) Cross section through the belt, showing low-resistivity, graphite-bearing lithologies (blue) and higher-resistivity nongraphitic units (reds and pinks). Semitransparent regions are below the depth-of-investigation provided by the data. (AEM data available from U.S. Geological Survey, 2024c).



Agency (DARPA) and Advanced Research Projects Agency-Energy (ARPA-E) initiated the Critical Mineral Assessment with Artificial Intelligence Support (CriticalMAAS) program (<https://www.darpa.mil/program/critical-mineral-assessments-with-ai-support>). The program's objective is to drastically reduce the amount of time required to conduct mineral resource assessments for materials critical for the energy transformation. The program expands on a machine-learning competition (USGS, 2022b) on automating georeferencing and feature extraction from geologic maps. In addition to the winners of the competition, teams representing small businesses, research institutions and universities are engaging in

critical mineral resource assessments from four technical areas, consisting of (1) extracting data from maps, (2) extracting knowledge from structured and unstructured source documents, (3) mineral prospectivity mapping and (4) human-in-the-loop interfaces. The 12-month program proceeds according to a milestone schedule including hackathon events focused on specific applications of the technical solutions to real-world assessment problems.

Airborne electromagnetic survey in Alabama. Earth MRI has accelerated acquisition of geophysical data over areas with the potential to contain critical mineral resources. Whereas the areas chosen for surveys under this program host mineral systems likely to contain critical minerals, the resulting geophysical maps and models are also being used for a range of geologic, hydrologic and hazard-related research.

To support an ongoing assessment of domestic graphite resources, the USGS conducted an airborne electromagnetic (AEM) survey of the Alabama Graphite-Vanadium Belt within the Southern Appalachian Mountains and surrounding regions (Fig. 3). Electromagnetic surveys are ideal for mapping graphite lithologies due to the extremely low resistivity (high conductivity) of graphite-bearing rocks. Graphite contents as low as 1 weight percent can drop bulk resistivity by orders of magnitude (to less than 1 $\Omega\cdot\text{m}$) relative to similar nongraphitic lithologies.

The AEM survey covered the mapped extent of the belt and beyond, permitting construction of a 3D model of subsurface electrical resistivity to depths in excess of 500 m. The model directly images the extent of graphite-bearing lithologies, the thickness of a surficial weathered graphite zone (the source of most historic mining), and the geometry of the belt itself (MacQueen et al., 2023). Additionally, extensions of the belt are imaged beneath the Coastal Plain and to the northeast of the traditionally defined belt. The resistivity model is further aiding geologic mapping efforts in this complex structural corridor where traditional geologic mapping is difficult. Finally, key subsurface structures and faults are revealed that inform the tectonic

evolution of the region and controls on mineralization.

International collaboration

The USGS continues active collaborations with international partners that support critical mineral resources research and investigate options that mitigate strategic mineral resource vulnerabilities. Recent collaboration efforts include work carried out in Algeria, Uzbekistan and Kazakhstan and the Critical Minerals Mapping Initiative (CMMI), an ongoing collaboration with Geoscience Australia and the Geological Survey of Canada. In the first two countries, multidisciplinary teams prepared quantitative and semiquantitative mineral resources assessment that emphasized critical minerals. The USGS also provided training to colleagues on various field and office techniques, including the three-part quantitative assessment method, as well as in geophysics, geochemistry, geochronology and remote sensing. A similar effort is just starting in Kazakhstan, to assist that country with their multiple interests in mineral exploration for critical minerals, the extraction of minerals from mine waste, and conventional and unconventional energy sources.

Critical Minerals Mapping Initiative. The broader goals of CMMI are to advance our collective understanding of critical mineral resources in Australia, Canada and the United States by engaging in data and knowledge sharing (Emsbo et al., 2021; Kelley, 2020). CMMI is continuing efforts to expand a unified Critical Minerals in Ores (CMiO) database (Champion et al., 2021) with additional modern geochemical data. Future updates of the database are planned to include analyses from approximately 20,000 samples from the USGS (Granitto et al., 2021) and the Geological Survey of Queensland using the mineral systems classification of Hofstra et al. (2021). CMMI continues to seek contributions from external sources to fill data gaps among deposits and deposit types, particularly in other foreign countries. As the CMiO database continues to grow, users can gain progressively better understanding of the distributions of critical minerals across systems and deposit types and deposits. These data can be used to guide future research on fundamental controls on critical mineral endowments.

Another effort of the CMMI collaboration has been developing critical mineral prospectivity methods that combine geologic, geophysical and temporal data using knowledge and data-driven approaches. The initial focus was on basin-hosted lead-zinc

deposits (Mississippi Valley-type and clastic dominated lead-zinc), which are present in all three countries, and contain other critical minerals, including gallium, germanium, indium and nickel. Knowledge-driven and data-driven modeling (Lawley et al., 2022) utilizes national-scale geologic and geophysical data and derivative layers, along with basin-hosted zinc-lead (Zn-Pb) mineral sites for Australia, Canada and the United States (McCafferty et al., 2023a). These data can be used as important underpinning evidence layers for regional- to national- to continental-scale prospectivity modeling and follow-on assessments. Some of the derivative products have already proven impactful within for USGS research, such as guiding Earth MRI targeting of areas for high-resolution magnetic and radiometric surveys (McCafferty et al., 2023b) and development of artificial intelligence/machine learning (AI/ML)-assisted prospectivity tools.

Byproduct critical mineral supply chains

Byproducts constitute a subset of critical minerals that depend on the production of a host mineral that may or may not be designated as a critical mineral and exist in sufficient quantities to be recovered during processing or refining. Understanding the supply chains of byproduct critical minerals necessitates knowledge of ore mineralogy and geochemical concentration, behavior of different minerals and elements during beneficiation and recovery processes, primary commodity production quantities, and trade flows of mined and intermediate products. Two case studies, focused on cobalt and rhodium, are summarized here as instructive examples for better understanding the supply risk and dynamics of byproduct critical minerals.

Cobalt. Demand for cobalt as a cathode material in various lithium-ion battery chemistries has nearly tripled from 2013 to 2023, with cobalt in batteries accounting for the majority of total usage. The rising demand for cobalt has raised concerns over ethical sourcing with governments, producers and end-users focusing on mining practices as part of an overall environmental, social and governance (ESG) effort. According to data compiled by the USGS, the Democratic Republic of the Congo (DRC) accounted for 74 percent of global mined cobalt production in 2023 (USGS, 2024a).

Since the collapse of the DRC copper-cobalt industry in the 1990s, a portion of DRC cobalt mine production has come from artisanal cobalt miners (Gulley, 2022). Research on artisanal cobalt mining has revealed human rights abuses,

Annual Review 2023: Critical Minerals

Figure 4

Increases in artisanal production follow price increases, underscoring the role of artisanal mining as a “swing producer.” Declines in artisanal production from 2010 to 2016 correspond to low cobalt prices (Gulley, 2023).

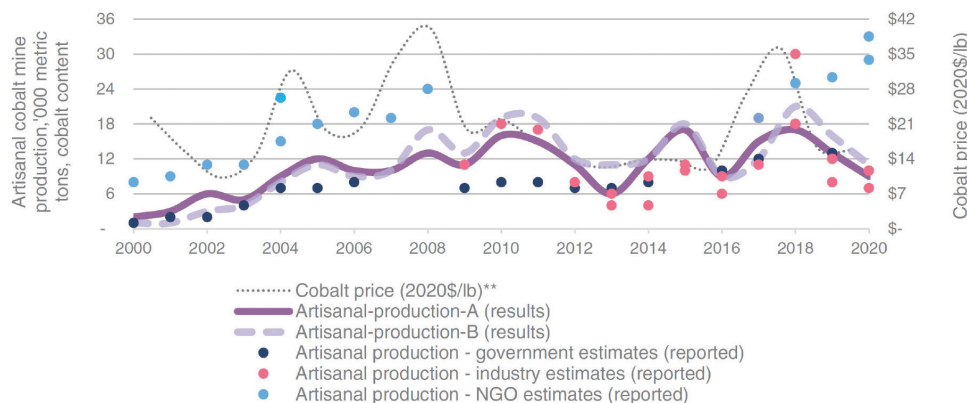


Figure 5

DRC artisanal production as a share of total DRC cobalt mine production and as a share of total world cobalt mine production (Gulley, 2023).

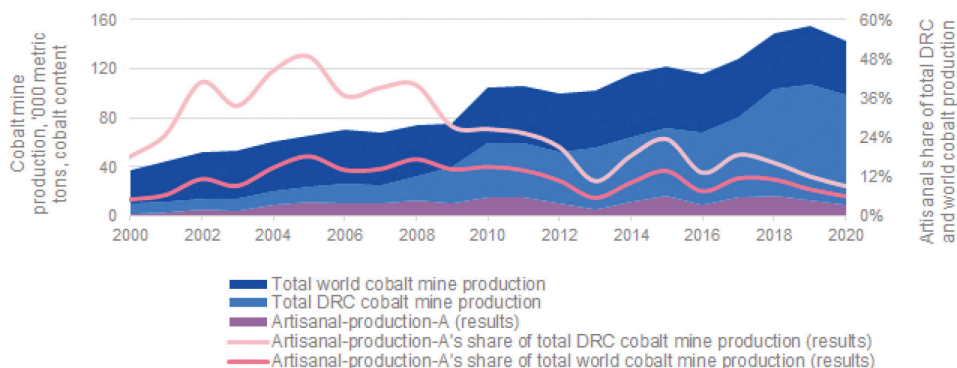
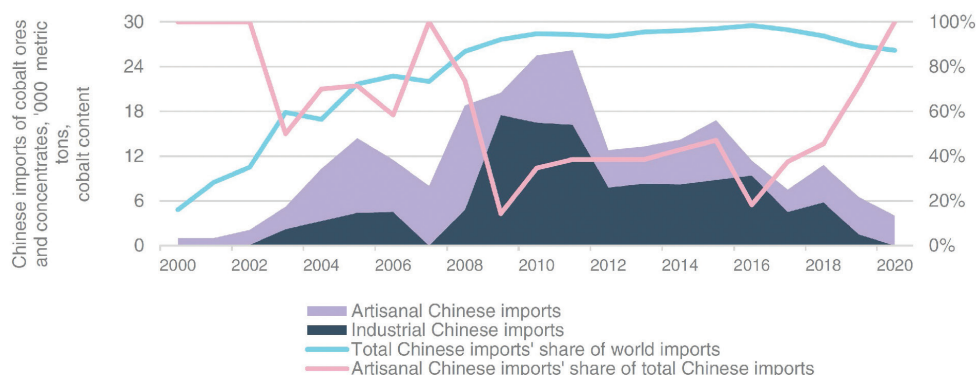


Figure 6

China's imports of cobalt ores/concentrates from the DRC along with China's share of world imports and the artisanal share of China's total imports (Gulley, 2023).



as well as forced and child labor (U.S. Department of Labor, 2024). Although key to addressing these issues, attempts to systematically quantify artisanal cobalt production or identify its destinations have proven elusive.

Building upon an earlier analysis of Congolese cobalt production since 1924, Gulley (2023) used data from the DRC government, mining companies, third-party data sources and international trade flows to estimate the production of cobalt from artisanal mines using two approaches. Method A calculated the difference between total reported cobalt production in the DRC and the reported production of so-called “industrial” or “large-scale” mines operating in the DRC. Industrial mines are formally organized companies that operate under license from the DRC government, are highly mechanized and employ a highly skilled work force. Method B consists of two components: (1) estimates of the quantity of artisanal cobalt production that is processed into intermediate cobalt products in the DRC, and (2) calculations of artisanal exports as the difference between total Chinese imports and exports of industrial cobalt from the DRC to China.

In the early 2000s, most of the industrial cobalt mines operating in the DRC were either owned by or under long-term contracts with Western companies (Gulley, 2022). The rapid growth of China's cobalt refinery sector in the period from 1999 through 2005 entailed the arrival of Chinese traders and processing companies to

the DRC in search of cobalt ore. Because most of the industrial cobalt ore/concentrate was locked into offtake agreements, Chinese entities turned to the informal sector to meet their feedstock requirements (Fig. 4).

Figure 5 shows how artisanal production shares of total DRC and world cobalt production peaked at 49 and 18 percent, respectively, in 2005 before trending down to 9 and 6 percent in 2020 (Gulley, 2023). In contrast, average nongovernmental-organization (NGO) estimates show peaks of DRC artisanal mines' shares at 93 and 31 percent, respectively, in 2004. For the years 2000 through 2006, the years when estimates from both NGOs and governments are available, NGO estimates are nearly four times larger than government estimates (Gulley, 2023).

Artisanal imports to China increased from 1 kt in 2000 to 14 kt in 2008 reflecting China's growing demand for feedstock for its refinery sector (Fig. 6). Artisanal imports started to trend down from a peak in 2010 as the DRC's industrial sector began to recover and reflects the rise of artisanal processing in the DRC in addition to increasing production of crude cobalt hydroxide in the DRC's industrial sector. The share of Chinese imports attributed to artisanal production averaged 39 percent from 2010 through 2017 as the DRC's industrial mining sector expanded production (Gulley, 2023). However, this share increased to 100 percent in 2020 as two DRC industrial miners ceased concentrate exports to produce crude cobalt hydroxide (Gulley, 2023). Despite the high share in 2020, the volume of China's imports of artisanal cobalt from the DRC was quite low by historical standards.

The USGS estimation results largely follow those of governments and industry. Specifically, the USGS results are on average 18 percent higher than those presented by governments and industry. In contrast, estimates of artisanal cobalt production in the DRC from NGOs are 2.2 to 3.1 times higher than those of government, industry or the USGS. Because artisanal mining represents between 9 and 11 percent of total DRC cobalt production, a random sampling of cobalt sourcing would mean that an end-user would have a 90 percent chance of sourcing from industrial (nonartisanal) sources, based on this analysis. According to seven in-person artisanal cobalt mine site studies published between 2017 and 2021 — the results of which the USGS re-reported as found and did not attempt to independently verify — children were present at roughly one in four artisanal cobalt mine sites studied. Given this estimate, and the results above, the chance of an end-user sourcing from

an artisanal producer using child labor may be as low as 2 percent. The large inconsistencies between different methods of estimation underscore the importance of thoroughly understanding cobalt supply-chain dynamics.

Rhenium. Rhenium is produced as a byproduct of copper and molybdenum and serves as a critical component in high-temperature alloys used in aerospace and gas power generation turbines. Rhenium has a particularly complex supply chain, because molybdenum is itself a byproduct of copper. Thus, rhenium is a “byproduct of a byproduct” and is subject to the market dynamics of both copper and molybdenum. Further, international trade in rhenium-bearing molybdenum concentrates adds yet another layer of intricacy to the rhenium supply chain.

Advances in superalloys used in high-temperature aerospace and energy applications have increased the demand for rhenium from essentially zero in the 1940s to approximately 75 tons in 2019 (Brainard, 2023). Despite its important end-uses, quantifying recoverable supplies of rhenium has proven difficult due to the difficulty of tracking primary production combined with the high level of aggregation of trade flows of rhenium.

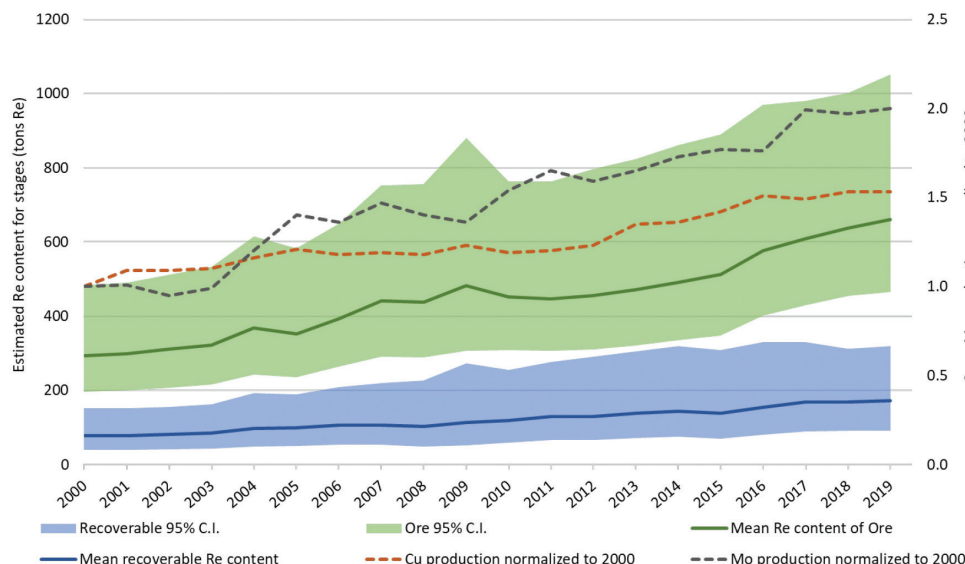
By compiling data on rhenium grade in deposits and in the flow of production and trade, estimates of rhenium supply are possible (Brainard, 2023). In brief, rhenium supply can be estimated through just a few pieces of information: (1) rhenium grade in the ore, (2) the annual production of the parent material and the recovery rate of rhenium from that production and (3) international trade flows of rhenium-bearing molybdenum and copper (Brainard, 2023). These estimation techniques have indicated that less than 12 percent of rhenium present in the ore is currently captured owing to technical recovery limits. Additional rhenium production beyond technical recovery limits may only be realized through increases in the mining of copper and molybdenum.

Data compiled by the USGS demonstrate a correlation between rhenium grade in whole rock and molybdenum grade (Brainard, 2023). This correlation permits estimates of rhenium grade of unknown deposits. For example, according to a regression analysis, molybdenum grading of 0.01 percent would correlate to a rhenium content of approximately 0.015 ppm (Brainard, 2023). It would therefore be reasonable to assign this rhenium content to other molybdenum deposits of similar grade but with an unknown (or unreported) rhenium

Annual Review 2023: Critical Minerals

Figure 7

Time series of rhenium content in ore (green line) and recoverable rhenium content (blue line) with 95 percent confidence intervals (C.I., shaded regions), compared to copper and molybdenum production (dotted lines, Brainard, 2023).



content. This estimate could be adjusted for uncertainty using a 95 percent confidence interval. The need for estimation is limited, however, because rhenium contents are reported for 70 percent of copper production and 80 percent of molybdenum production (Brainard, 2023). The data in Fig. 7 represent only available reported data and data for China adjusted by using the mid-point based on the composition of all Chinese molybdenum deposits to account for “missing” molybdenum production. Shaded regions represent the range of the rhenium

data 95 percent confidence intervals. Production of copper (orange dashed) and molybdenum (gray dashed) are added for comparison of rhenium with host commodity growth, where production is normalized to production in 2000 (that is, two would be twice the production in 2000).

The next step in determining rhenium supplies is to assess the quantities of rhenium embedded in international trade flows of copper and molybdenum. This is important because the countries that mine copper and/or molybdenum do not always liberate the rhenium contained therein (Brainard, 2023). Therefore, tracking international trade flows of copper concentrates and unroasted molybdenum concentrates is essential for a comprehensive quantitative assessment of rhenium availability. Once the rhenium content of these trade flows is known, net imports can be added to domestic production to get an estimate of a country’s apparent consumption of rhenium (Fig. 8). From another perspective, apparent consumption informs the amount of rhenium available to a nation post-trade.

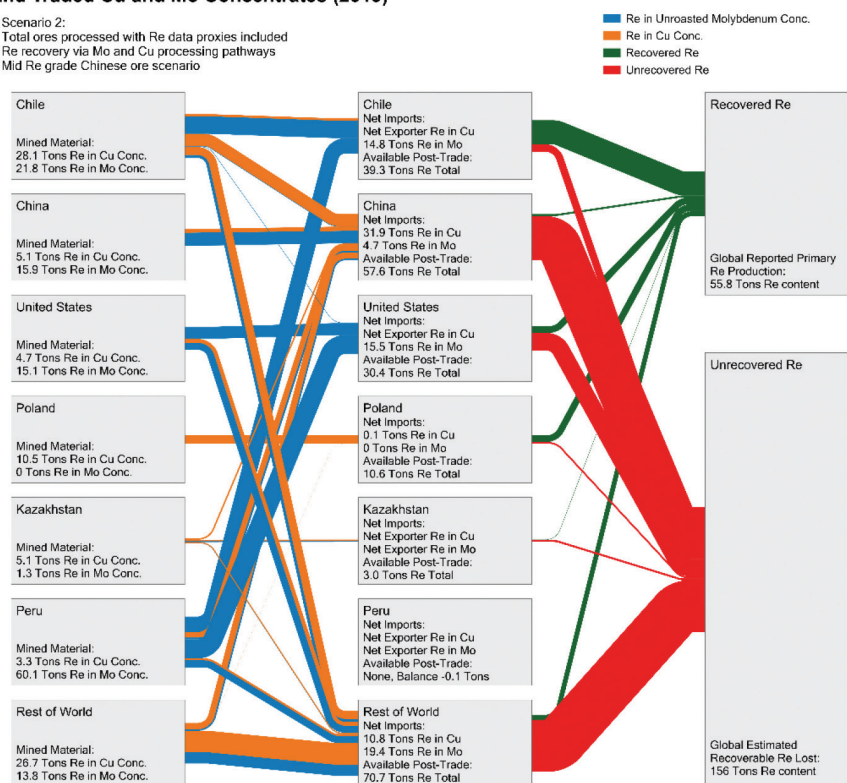
The key takeaway from the trade data is that only a few nations participate in the mining, trade and roasting of copper and molybdenum concentrates to extract rhenium. In

Figure 8

Diagram of rhenium material flows by country, form and processing stage (Brainard, 2023).

Technically Recoverable Rhenium Content of Mined and Traded Cu and Mo Concentrates (2019)

Scenario 2:
Total ores processed with Re data proxies included
Re recovery via Mo and Cu processing pathways
Mid Re grade Chinese ore scenario



other words, the supply and potential supply of rhenium undergoes significant redistribution due to these trade flows. Chile, for example, is involved in all three aspects (mining, importing concentrates, roasting), whereas Peru simply exports all its rhenium-bearing molybdenum (Brainard, 2023). Due to these idiosyncrasies, assessment of a country's rhenium extraction potential should be conducted post-trade (Brainard, 2023).

The USGS's work on estimating accessible rhenium supply helps fill a knowledge gap between reported rhenium production and what is theoretically possible from both known and unknown deposits.

These estimates could be improved through greater transparency from mining and processing companies that currently treat these data as proprietary. Given the criticality of rhenium and other byproduct minerals, an accurate assessment of available supply is essential for sound policy and investment decisions.

Conclusion

Through various research activities across critical mineral supply chains, USGS contributions help to define the nation's critical mineral supply chain issues, acquire the fundamental data needed to address these problems, and provide authoritative information needed to guide policy decisions. Considering the high priority of critical minerals to economic and national security as well as the energy transformation, critical minerals research and assessments remain key components of the overall USGS mission. The application of geoscience information to societal issues is of paramount importance to the stewardship of natural resources and decision-making on behalf of future generations. ■

Disclaimer

Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Brainard, J.L., 2023, The availability of primary rhenium as a by-product of copper and molybdenum mining: Mineral Economics, <https://doi.org/10.1007/s13563-023-00392-0>

Champion, D., Raymond, O., Huston, D., VanDerWielen, S., Sexton, M., Bastrakov, E., Schroder, I., Butcher, G., Hawkins, S., Lane, J., McAlpine, S., Czarnota, K., Britt, A., Granitto, M., Hofstra, A., Kreiner, D., Emsbo, P., Kelley, K., Wang, B., Case, G., Graham, G., Lauzière, K., Lawley, C., Gadd, M., Pilote, J.-L., Létourneau, F., Lisitsin, V., and Haji Egeh, A., 2021. Critical Minerals in Ores— geochemistry database. Geoscience Australia, Canberra, <https://pid.geoscience.gov.au/dataset/ga/145496>

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>

Drenth, B.J., and Grauch, V.J.S., 2019, Finding the gaps in America's magnetic maps: Eos, American Geophysical Union, 100, <https://doi.org/10.1029/2019EO120449>

Emsbo, P., Lawley, C., and Czarnota, K., 2021, Geological surveys unite to improve critical mineral security: Eos, American Geophysical Union, 102, <https://doi.org/10.1029/2021EO154252>

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>

Gulley, A.L., 2022, One hundred years of cobalt production in the Democratic Republic of the Congo: Resources Policy, v. 79, p. 103007, <https://doi.org/10.1016/j.resourpol.2022.103007>

Gulley, A.L., 2023, China, the Democratic Republic of the Congo, and artisanal cobalt mining from 2000 through 2020: Proceedings of the National Academy of Sciences, v. 120, no. 26, p. e2212037120, <https://doi.org/10.1073/pnas.2212037120>

Hammarstrom, J.M., Woodruff, L.G., and Dicken, C.L., 2023, Critical mineral deposits of the United States: U.S. Geological Survey data release, <https://doi.org/10.5066/P9K1HBNT>

Hofstra, A.H., and Kreiner, D.C., 2020, Systems-Deposits-Commodities-Critical Minerals Table for the Earth Mapping Resources Initiative (ver. 1.1, May 2021): U.S. Geological Survey Open-File Report 2020–1042, 26 p., <https://doi.org/10.3133/ofr20201042>

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>

Hubbard, B.E., Gallegos, T.J., and Stengel, V.G., 2023, Mapping abandoned uranium mine features using Worldview-3 imagery in portions of Karnes, Atascosa and Live Oak Counties, Texas: Minerals, v. 13, no. 7, 839, <https://doi.org/10.3390/min13070839>

Hubbard, B.E., Gallegos, T.J., Stengel, V.G., Hoefen, T.M., Kokaly, R.F., and Elliot, B., 2024, Hyperspectral (VNIR-SWIR) analysis of roll front uranium host rocks and industrial minerals from Karnes and Live Oak Counties, Texas Coastal Plain: Journal of Geochemical Exploration, v. 247, 20 p., <https://doi.org/10.1016/j.gexplo.2023.107370>

Kelley, K.D., Scott, C.T., Polyak, D.E., and Kimball, B.E., 2017, Vanadium, chap. U of Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, p. U1–U36, <https://doi.org/10.3133/pp1802U>

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>

Kelly, T.D., and Matos, G.R., comps., 2014, Historical statistics for mineral and material commodities in the United States (2016 version): U.S. Geological Survey Data Series 140, <https://www.usgs.gov/centers/national-minerals-information-center/historical-statistics-mineral-and-material-commodities>

Kreiner, D.C., Hammarstrom, J., and Day, W., 2023, Critical minerals for a carbon-neutral future:

Annual Review 2023: Critical Minerals

Eos, American Geophysical Union, 104, <https://doi.org/10.1029/2023EO230403>

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>

MacQueen, P., Bedrosian, P., Hoogenboom, B.E., Gustafson, C., Bollen, E. and Whitmore, J.P., 2023, Earth MRI airborne electromagnetic survey reveals graphite potential and tectonic complexity of the Alabama graphite-vanadium belt [abst.]: *Geological Society of America Abstracts with Programs*, v. 55, no. 6, <https://doi.org/10.1130/abs/2023AM-391604>

McCafferty, A.E., San Juan, C.A., Lawley, C.J.M., Graham, G.E., Gadd, M.G., Huston, D.L., Kelley, K.D., Paradis, S., Peter, J.M., and Czarnota, K., 2023a, National-scale geophysical, geologic, and mineral resource data and grids for the United States, Canada, and Australia: Data in support of the tri-national Critical Minerals Mapping Initiative: U.S. Geological Survey data release, <https://doi.org/10.5066/P970GDD5>

McCafferty, A.E., Amaral, C.M., and Graham, G.E., 2023b, National- to continental-scale governmental geophysical efforts for critical mineral mapping, USA [abst.]: *Society for Geology Applied to Mineral Deposits Biennial Meeting abstracts*, v. 3, p. 363-367, <https://e-sga.org/nc/publications/sga-biennial-meetings-abstract-volumes/2023-zurich/>

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: U.S. Geological Survey Open-File Report 2021-1045, 31 p., <https://doi.org/10.3133/ofr20211045>

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., 2020, Evaluating the mineral commodity supply risk of the U.S. manufacturing sector: *Science Advances*, v. 6, no. 8, article eaay8647, 12 p., <https://doi.org/10.1126/sciadv.aay8647>

Shah, A.K., Morrow, R.H., Pace, M.D., Harris, M.S., and Doar, W.R., 2021, Mapping critical minerals from the sky: *Geological Society of America Today*, v. 31, no. 1, p. 4-10, <https://doi.org/10.1130/GSATG512A.1>

U.S. Department of Labor, 2024, Combatting Child Labor in the Democratic Republic of the Congo's Cobalt Industry (COTECCO), <https://www.dol.gov/agencies/ilab/combating-child-labor-democratic-republic-congos-cobalt-industry-cotecco>

U.S. Geological Survey, 2022a, 2022 Final List of Critical Minerals, Federal Register, v. 87, no. 37, p. 10381-10382, <https://www.federalregister.gov/documents/2022/02/24/2022-04027/2022-final-list-of-critical-minerals>

U.S. Geological Survey, 2022b, DARPA Announces Winners of Artificial Intelligence Competition to Aid Critical Minerals Assessments: U.S. Geological Survey press release, accessed March 6, 2024 at <https://www.usgs.gov/news/technical-announcement/darpa-announces-winners-artificial-intelligence-competition-aid>

U.S. Geological Survey, 2023a, Mineral commodity summaries 2023: U.S. Geological Survey, 210 p., <https://doi.org/10.3133/mcs2023>

U.S. Geological Survey, 2023b, USGS makes \$5 million available from the Bipartisan Infrastructure Law for mine waste research: U.S. Geological Survey press release, accessed 02 March 2024, at <https://www.usgs.gov/news/national-news-release/usgs-makes-5-million-available-bipartisan-infrastructure-law-mine-waste>

U.S. Geological Survey, 2024a, Mineral commodity summaries 2024: U.S. Geological Survey, 212 p., <https://doi.org/10.3133/mcs2024>

U.S. Geological Survey, 2024b, Airborne magnetic and radiometric survey, South Pass-Granite Mountains region, Wyoming, 2023: U.S. Geological Survey data release, <https://doi.org/10.5066/P13W5Y9W>

U.S. Geological Survey, 2024c, Airborne electromagnetic and magnetic survey of the Alabama Graphite-Vanadium Belt and surrounding regions, 2023: U.S. Geological Survey data release, <https://doi.org/10.5066/P1F7PFSF>

Vikre, P., John, D., Wintzer, N.E., Koutz, F., Graybeal, F., Dail, C., and Annis, D.C., 2023, Critical minerals in subduction-related magmatic-hydrothermal systems of the United States: U.S. Geological Survey Scientific Investigations Report 2023-5082, 110 p., <https://doi.org/10.3133/sir20235082>

Wang, C., Slack, J.F., Shah, A.J., Yates, M.G., Lentz, D.R., Whittaker, A.T.H., and Marvinney, R.G., 2023, A recently discovered trachyte-hosted rare earth element-niobium-zirconium occurrence in northern Maine, USA: *Economic Geology*, v. 118, p. 1-13, <https://doi.org/10.5382/econgeo.4993>

Watts, K.E., Haxel, G.B., and Miller, D.M., 2022, Temporal and petrogenetic links between Mesoproterozoic alkaline and carbonatite magmas at Mountain Pass, California. *Economic Geology*, v. 117, p. 1-23, <https://doi.org/10.5382/econgeo.4848>

Watts, K. E., Miller, D. M., and Ponce, D.A., 2024, Mafic alkaline magmatism and rare earth element mineralization in the Mojave Desert, California: The Bobcat Hills connection to Mountain Pass. *Geochemistry, Geophysics, Geosystems*, v. 25, e2023GC011253, <https://doi.org/10.1029/2023GC011253>

Woodruff, L.G., Hammarstrom, J.H., and Dicken, C.L., 2023, A new compilation of past, current, and possibly future critical mineral deposits across the United States: A companion to Earth MRI focus area [abst.]: *Geological Society of America Abstracts with Program*, v. 55, no. 6., <https://gsa.confex.com/gsa/2023AM/webprogram/Paper391140.html>

upcoming events



NAT 2024
NORTH AMERICAN
TUNNELING CONFERENCE

North American Tunneling Conference
June 23-26, 2024 | Nashville, TN



SME 43 ICGCM
International Conference on Ground Control in Mining

International Conference on Ground Control in Mining
July 22-25, 2024 | Canonsburg, PA



SME IMPC 2024
XXXI International Mineral Processing Congress

IMPC-International Mineral Processing Congress
Sept. 29-Oct. 3, 2024 | National Harbor / Washington, D.C.