USGS critical minerals review

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Supply chain disruptions across multiple sectors of the U.S. economy have become a highly visible challenge as the United States moves through and out of the COVID-19 pandemic (World Economic Forum, 2022). In addition to the pandemic, trade wars, natural disasters and more recently, open military conflict, have caused major, systemic stresses to U.S. mineral raw material supply chains (Shih, 2020), which over the past several decades have become steadily more global and reliant on imports (Fortier et al., 2015). In 2021, the U.S. Geological Survey (USGS) continued to play a central role in understanding and anticipating potential supply chain disruptions by defining and quantitatively evaluating mineral criticality. In addition, the USGS continued to evaluate new sources of domestic critical minerals by conducting mineral resource assessments, mapping and surveying regions prospective for critical minerals, re-assessing mine waste and pursuing fundamental research in support of responsible, sustainable mining.

The Fiscal Year (FY) 2022 Bipartisan Infrastructure Law (BIL) substantially increased funding for the USGS Earth Mapping Resources Initiative (Earth MRI) to $320 million over a five-year period. Congress stated that the purpose of Earth MRI "shall be to accelerate efforts to carry out the fundamental resources and mapping mission of the United States Geological Survey by: (1) providing integrated topographic, geologic, geochemical, and geophysical mapping; (2) accelerating the

Figure 1

Map of the global distribution of gold operations and a bar plot of the cumulative share of total global gold production. Each individual operation is plotted as a single circle on the map and a single bar on the plot. The colors of the circles indicate individual rock-to-metal ratios (RMRs), which range from a low of 1×10^5 to a high of 2.2×10^8 and yield a global weighted average RMR of 3×10^6 (n = 777). The sizes of the circles are proportional to an operation's share (in percent) of total global gold production, ranging from a low of <0.001 percent to a high of 2.6 percent for a total global coverage of 79 percent of 2018 global gold production (U.S. Geological Survey, 2020). Operations are ordered from lowest to highest RMR on the bar plot (Nassar et al., 2022).

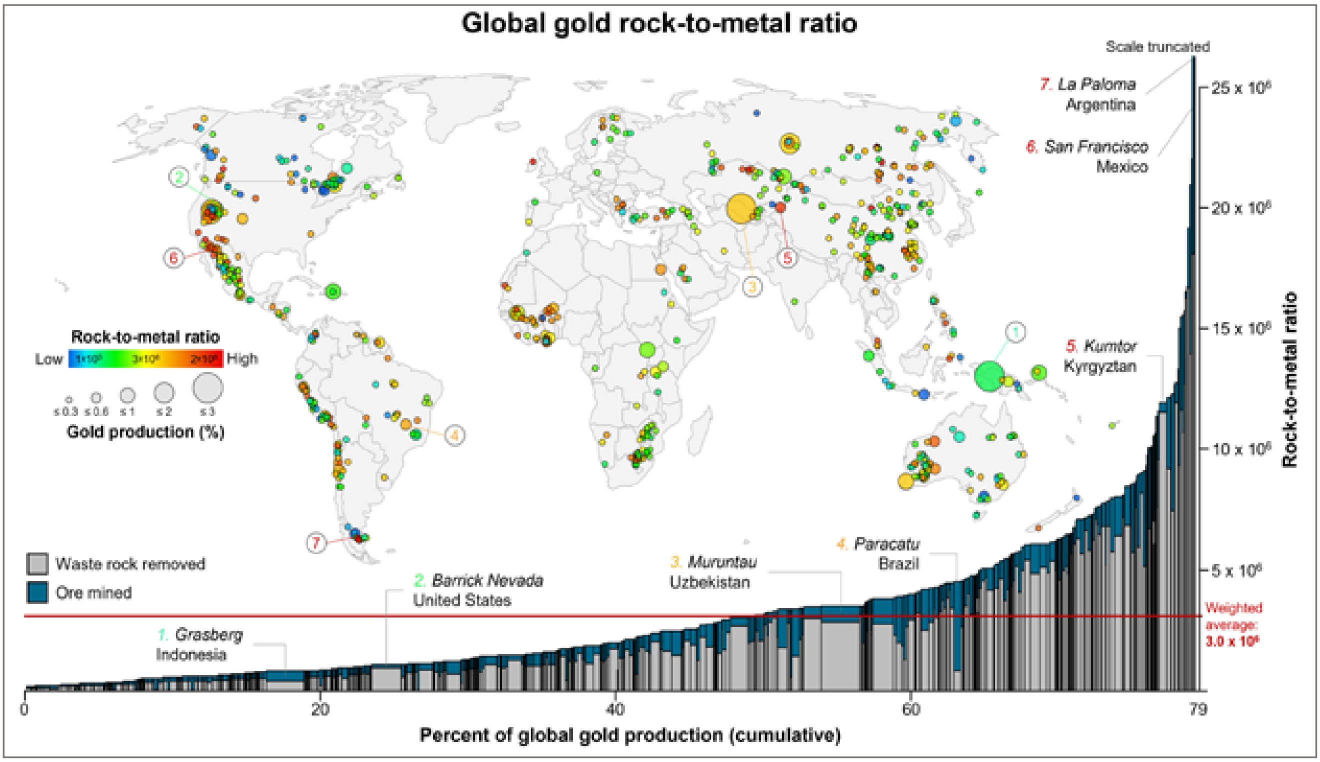
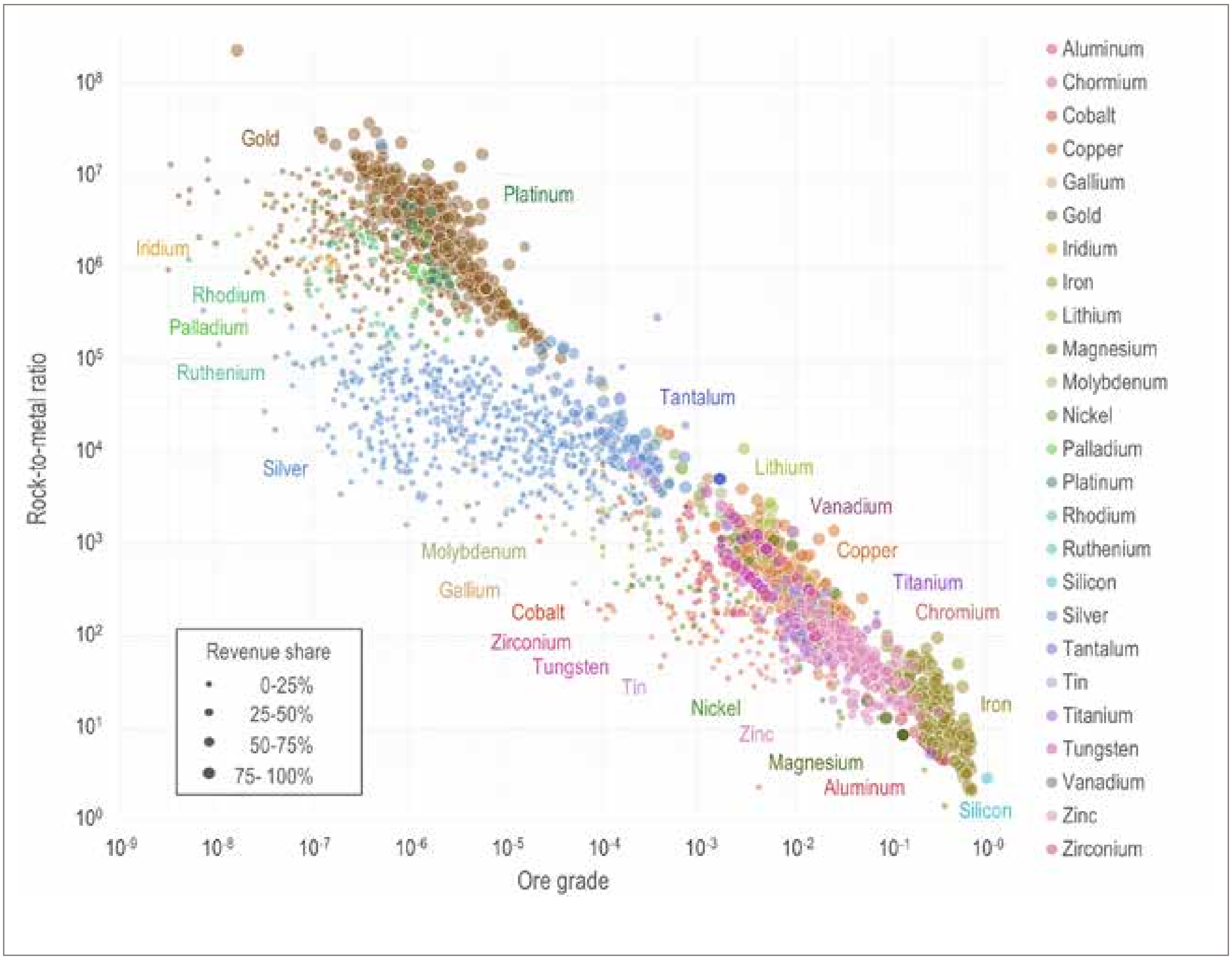


Figure 2

Rock-to-metal ratio (vertical axis) versus ore grade (horizontal axis) by mineral commodity by individual operation. Axes are on a $\log_{10}$-$\log_{10}$ scale. Colors correspond to different commodities. Marker size corresponds to revenue share (economic allocation) attributable to the mineral commodity at the specific operation (Nassar et al., 2022).



integration and consolidation of geospatial and resource data; and (3) providing interpretation of subsurface and above-ground mineral resources data." This increase in funding for Earth MRI provides a transformational opportunity for the geoscience community to produce new detailed geologic maps and conduct regional reconnaissance geochemical surveys on mineral systems that are widely dispersed across regional terranes; it offers the unique opportunity to collect large regional airborne geophysical surveys, enhances funding for lidar to support geologic mapping, and expands the role of the USGS and partners to examine the critical mineral abundances in mine waste materials.

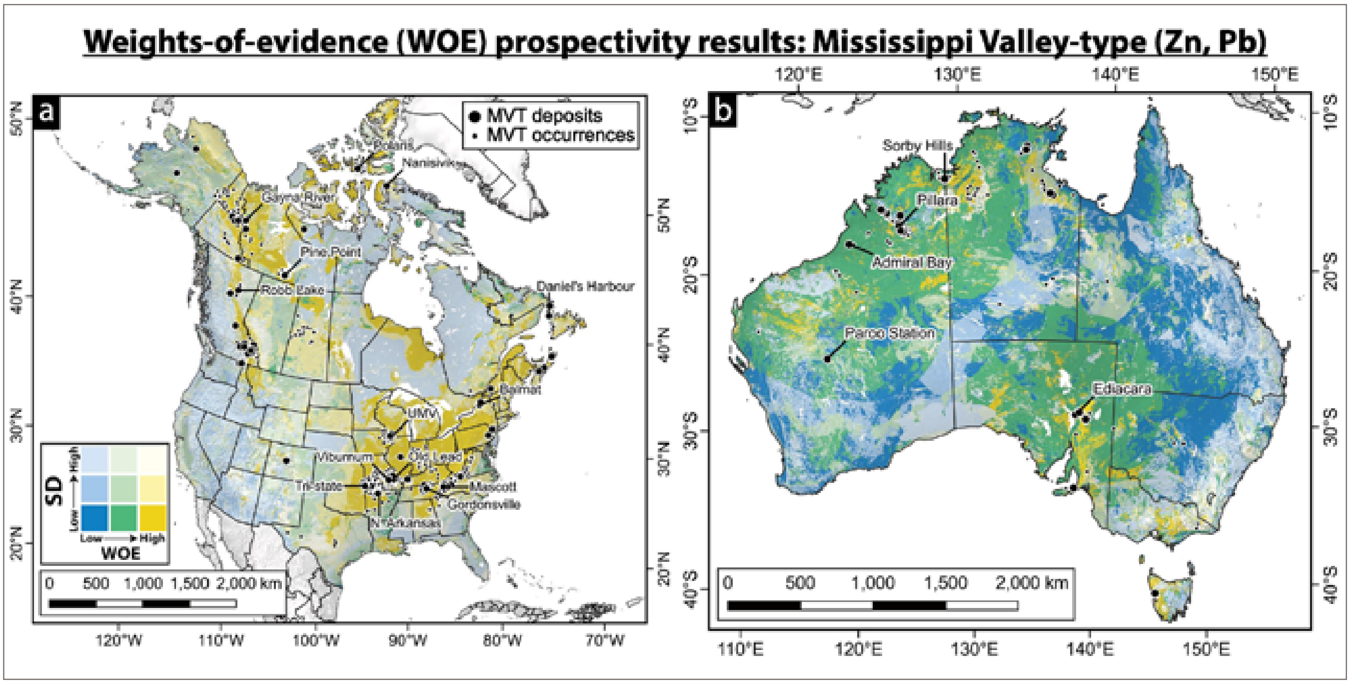
Mineral criticality: Update of the 2018 Critical Minerals List

Pursuant to Section 7002 (Mineral Security) of Title VII "Critical Minerals" of the Energy Act of 2020, the Secretary of the Interior, acting through the Director of the USGS, was tasked with reviewing and revising the methodology used to evaluate mineral criticality and updating the U.S. critical minerals list (CML) no less than every three years. The initial CML was published in the Federal Register on May 18, 2018, in response to Executive Order 13817: A Federal Strategy to Ensure the Secure and Reliable Supplies of Critical Minerals. The USGS published a report entitled "Methodology and Technical Input for the Review and Revision of the U.S. Critical Minerals List – 2021" on May 7, 2021 (Nassar and Fortier, 2021) to fulfill the methodology requirement of the Energy Act of 2020.

The methodology for identifying nonfuel mineral commodities as "critical" involves a quantitative assessment based on a risk modelling framework in which commodities with the greatest supply risk were those for which (1) global production was concentrated in countries that may become unable or

Figure 3

Updated weights-of-evidence (WOE) models for Mississippi Valley-type (Zn, Pb) deposits for: (a) Canada and the United States (UMV = Upper Mississippi Valley district) and (b) Australia. Bivariate colors are based on quantile scaling of the sum and standard deviation (SD) of the WOE-transformed datasets. Regions that yield high WOE prospectivity scores and low standard deviation represent the highest priority for mineral exploration targeting (dark yellow) (Lawley et al., 2022).



unwilling to continue to supply to the United States; (2) U.S. consumption was predominantly dependent on foreign supplies; and (3) U.S. consumption represented a large expenditure for U.S. manufacturing industries with low profitability but which contributed greatly to the U.S. economy. This quantitative assessment was based on a recently published approach for assessing the supply risk to the U.S. manufacturing sector (Nassar et al., 2020) and represents an enhancement of the original metrics used to generate the initial CML. A quantitative threshold based on objective criteria was also established to identify which commodities should be recommended for inclusion on the CML. Commodities for which the necessary data to perform the quantitative assessment were not available were assessed semi-quantitatively or qualitatively based on available information.

In addition to the quantitative assessment, which focused on foreign supply disruptions, an evaluation of domestic supplies was also performed. Specifically, commodities with only a single domestic producer at any node in the supply chain were identified as having a single point of failure and were automatically recommended for inclusion on the CML.

A total of 54 mineral commodities had sufficient data to be analyzed using the quantitative assessment. These 54 mineral commodities included seven individual rare earths elements (REEs) and five platinum-group metals (PGMS), which were analyzed as groups in the initial CML. Pursuant to the Energy of Act of 2020, the following were explicitly excluded from consideration in this analysis: water, fuel minerals, and common varieties of industrial minerals, such as sand, gravel, stone, pumice, cinders and clay.

Of the 54 mineral commodities analyzed using the quantitative assessment, 36 met the quantitative threshold criteria. In rank order from highest to lowest based on a recency-weighted mean of their overall supply risk scores, these commodities were: gallium, niobium, cobalt, neodymium, ruthenium, rhodium, dysprosium, aluminum, fluorspar, platinum, iridium, praseodymium, cerium, lanthanum, bismuth, yttrium, antimony, tantalum, hafnium, tungsten, vanadium, tin, magnesium, germanium, palladium, titanium, zinc, graphite, chromium, arsenic, barite, indium, samarium, manganese, lithium and tellurium (Nassar and Fortier, 2021). Three commodities were also recommended for inclusion on the CML based on the single point of failure criterion: beryllium, nickel and zirconium. Three commodities on the initial CML, cesium, rubidium, scandium, as well as the other REEs (europium, gadolinium, terbium, holmium, erbium, thulium, ytterbium and lutetium) were not evaluated using the quantitative method due to insufficient data. Based on a qualitative evaluation of their supply and demand, none of these commodities were recommended for removal from the CML. Overall, of the commodities evaluated, two commodities not on the initial CML were recommended for inclusion (nickel and zinc) and four on the initial CML (helium, potash, rhenium and strontium) did not meet either the quantitative assessment or the single point of failure criteria. Uranium was not included in the analysis based on its definition as a mineral fuel in the Mining and Minerals Policy Act of 1970, and the language excluding fuel minerals from the definition of a critical mineral in the Energy Act of 2020. The final list of critical minerals was posted to the Federal Register on Feb. 24, 2022, following a 60-day public comment period and a 45-day review of all comments received (Federal Register, 2022). The mineral commodities evaluated for the original CML, the review and revision of the CML, the recommendations for inclusion or exclusion on the revised list, the basis for the recommendation, and whether it was included on the on the original CML, are shown in Table 1.

Mining sustainability: Development of quantitative rock-to-metal ratios

As the transition to renewable energy generation, electric vehicles and their associated storage technologies increases the demand for many critical mineral commodities, it is important to consider the full life-cycle environmental impacts of the mining and processing of these commodities. A clean energy vehicle cannot be ‘clean’ if it does more environmental harm that its internal combustion alternative. Life cycle assessment (LCA) is an appropriate and comprehensive tool to perform such a comparison (Guinée et al.,2011) and results from recent LCA research (Wolfram et al., 2021) reaffirms that electric vehicles have lower direct and indirect carbon emissions.

Accurate, thorough LCAs are extremely data intensive. Yet, when examining the life cycle inventory (LCI) data that go into LCAs it is commonly the case that these are based on data which are out of date or from only one or two operations, and hence may not be representative of actual impacts. This is the case for most commercial LCI datasets that are the basis for assessing the environmental impacts of mineral extraction and processing (Althaus and Classen, 2005; Frischknecht et al., 2005). Although these LCIs may provide a generally reasonable assessment of the environmental impacts when mineral commodities are a small component of a larger consumer product, they may not adequately capture the variability that exists between different mining and processing operations. The USGS, in collaboration with the U.S. technology company, Apple, Inc. (any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government) conducted a study to improve on this situation by investigating the variability in how much ore must be mined and waste rock (overburden) must be removed to produce a refined unit of a mineral commodity — its rock-to-metal ratio (RMR) (Nassar et al., 2022).

The RMR study analyzed 25 mineral commodities that spanned the base, precious and technology metals. The ore and waste extracted were allocated based on revenue contribution for operations in which multiple commodities were produced. The results indicate that the RMR for precious metals were in the range of 10^5-10^6, while base metals such as copper were on the order of 10^2-10^3 and commodities such as iron ore and aluminum were on the order of 10^1 The results also indicate significant variability across operations for a single commodity. The RMRs for gold, for example, ranged from a low of 1.0×10^5 to a high of 2.2×10^8 and yielded a global weighted average RMR of 3.0×10^6 (Fig. 1).

These results suggest that to produce 1 gram of refined gold requires, on average, 3 Mt (3.3 million st) of ore to be mined and waste rock to be removed, but that number could be as low as 0.1 or as high as 220 Mt (242 million st) depending on the operation. Indeed, across the nearly 2000 operations encompassing the 25 mineral commodities analyzed, the RMR spanned eight-orders of magnitude. Not surprisingly, ore grade was the primary factor impacting RMR, followed by revenue allocation (Fig. 2).

In addition to providing the RMR, the study quantified the total attributable material (ore mined and waste rock removed) for each of the 25 mineral commodities. The total across all commodities analyzed, after adjusting for global coverage, summed to 37.6 Gt (41.4 billion st), 83 percent of which can be attributable to only three commodities: iron ore, copper and gold (Nassar et al., 2022).

The RMR is not, by itself, a true environmental indicator as not all mine wastes are created equal, in terms of environmental impact. Nevertheless, RMR can provide

Table 1

2022 critical minerals list (CML) review, revision, rank and recommendations. Commodities that were not evaluated using the quantitative assessment are not given a rank and are ordered alphabetically.

Quantitative rank	Mineral commodity	Recommended for 2022 CML?	Basis for recommended inclusion on 2022 list	On 2018 CML?
1	Gallium	Yes	Quantitative assessment	Yes
2	Niobium	Yes	Quantitative assessment	Yes
3	Cobalt	Yes	Quantitative assessment	Yes
4	Neodymium	Yes	Quantitative assessment	Yes
5	Ruthenium	Yes	Quantitative assessment	Yes
6	Rhodium	Yes	Quantitative assessment	Yes
7	Dysprosium	Yes	Quantitative assessment	Yes
8	Aluminum	Yes	Quantitative assessment	Yes
9	Fluorspar	Yes	Quantitative assessment	Yes
10	Platinum	Yes	Quantitative assessment	Yes
11	Iridium	Yes	Quantitative assessment	Yes
12	Praseodymium	Yes	Quantitative assessment	Yes
13	Cerium	Yes	Quantitative assessment	Yes
14	Lanthanum	Yes	Quantitative assessment	Yes
15	Bismuth	Yes	Quantitative assessment	Yes
16	Yttrium	Yes	Quantitative assessment	Yes
17	Antimony	Yes	Quantitative assessment	Yes
18	Tantalum	Yes	Quantitative assessment	Yes
19	Hafnium	Yes	Quantitative assessment	Yes
20	Tungsten	Yes	Quantitative assessment	Yes
21	Vanadium	Yes	Quantitative assessment	Yes
22	Tin	Yes	Quantitative assessment	Yes
23	Magnesium	Yes	Quantitative assessment	Yes
24	Germanium	Yes	Quantitative assessment	Yes
25	Palladium	Yes	Quantitative assessment	Yes
26	Titanium	Yes	Quantitative assessment	Yes
27	Zinc	Yes	Quantitative assessment	No
28	Graphite	Yes	Quantitative assessment	Yes
29	Chromium	Yes	Quantitative assessment	Yes
30	Arsenic	Yes	Quantitative assessment	Yes
31	Barite	Yes	Quantitative assessment	Yes
32	Indium	Yes	Quantitative assessment	Yes
33	Samarium	Yes	Quantitative assessment	Yes
34	Manganese	Yes	Quantitative assessment	Yes
35	Lithium	Yes	Quantitative assessment	Yes
36	Tellurium	Yes	Quantitative assessment	Yes

Quantitative rank	Mineral commodity	Recommended for 2022 CML?	Basis for recommended Inclusion on 2022 list	On 2018 CML?
37	Lead	No	N/A	No
38	Potash	No	N/A	Yes
39	Strontium	No	N/A	Yes
40	Rhenium	No	N/A	Yes
41	Nickel	Yes	Single point of failure	No
42	Copper	No	N/A	No
43	Beryllium	Yes	Single point of failure	Yes
44	Feldspar	No	N/A	No
45	Phosphate	No	N/A	No
46	Silver	No	N/A	No
47	Mica	No	N/A	No
48	Selenium	No	N/A	No
49	Cadmium	No	N/A	No
50	Zirconium	Yes	Single point of failure	Yes
51	Molybdenum	No	N/A	No
52	Gold	No	N/A	No
53	Helium	No	N/A	Yes
54	Iron ore	No	N/A	No
	Cesium	Yes	Qualitive evaluation	Yes
	Erbium	Yes	Qualitive evaluation	Yes
	Europium	Yes	Qualitive evaluation	Yes
	Gadolinium	Yes	Qualitive evaluation	Yes
	Holmium	Yes	Qualitive evaluation	Yes
	Lutetium	Yes	Qualitive evaluation	Yes
	Rubidium	Yes	Qualitive evaluation	Yes
	Scandium	Yes	Qualitive evaluation	Yes
	Terbium	Yes	Qualitive evaluation	Yes
	Thulium	Yes	Qualitive evaluation	Yes
	Uranium	N/A	N/A	Yes
	Ytterbium	Yes	Qualitive evaluation	Yes

an additional dimension for evaluating the impact of mineral commodities and material choice trade-offs. Moreover, the RMR metric could significantly enhance LCIs when fully incorporated. Such metrics can be used by companies to monitor the environmental impacts of the materials used in their products and to quantify improvements achieved, for example, by shifting to the use of greater quantities of recycled materials.

Supply chain risk mitigation: Collaboration with reliable trade partners

Collaboration with allied countries to mitigate strategic and critical mineral vulnerabilities is a consistent theme, either explicitly or implicitly, in all recent U.S. government policy guidance documents (e.g. Executive Order 14017, 2021). The Critical Mineral Mapping Initiative (CMMI) is an ongoing example of such collaboration between the USGS, Geoscience Australia, and the

Geologic Survey of Canada, with the goal of understanding critical mineral resources in all three countries (Kelley, 2020; Kelley et al., 2021; Emsbo et al., 2021). This collaborative effort, initiated in 2019, builds upon existing datasets to understand critical mineral abundances in different deposit types, and promotes beneficial advancements in critical minerals science through data and expertise sharing.

Several important products have come out of the CMMI collaboration in 2021 including the release of the first version of a global digital database (Geoscience Australia, 2021). This database includes geochemical analyses of >7,300 rock and ore samples from around the world for as many as ~65 geochemical parameters, including most of the critical elements. Each of these samples has been classified using a unified deposit classification scheme developed as part of the trilateral effort (Hofstra et al., 2021). This schema is essential for efficient investigation and analysis of these geochemical data, particularly for critical elements in different deposit types. CMMI intends for this product to be a "living" database, with periodic updates to expand our knowledge of the chemistry of ore deposits in the three nations and across the globe, ultimately increasing our understanding of the distribution and concentration of critical metals.

CMMI collaboration has also facilitated the evaluation of critical mineral prospectivity and resource assessments. Specifically, prospectivity modelling of basin-hosted Zn-Pb deposits, including Mississippi Valley Type and clastic-dominated deposits, is a current focus for CMMI. These deposit types, which are found in all three partner countries, have the potential to host significant concentrations of critical minerals, including Ga, Ge and In, in addition to zinc, which was recently added to the 2022 U.S. critical minerals list (Federal Register, 2022). A

Figure 4

Preliminary outline of FY 2022 Earth MRI-funded airborne electromagnetic (AEM) surveys (outlined in red) and airborne magnetic (MAG) and radiometric (RAD) surveys (outlined in green) for areas of interest that contain areas permissive for hosting critical mineral resources. The final survey areas of interest are to be determined based on partner input and cost.

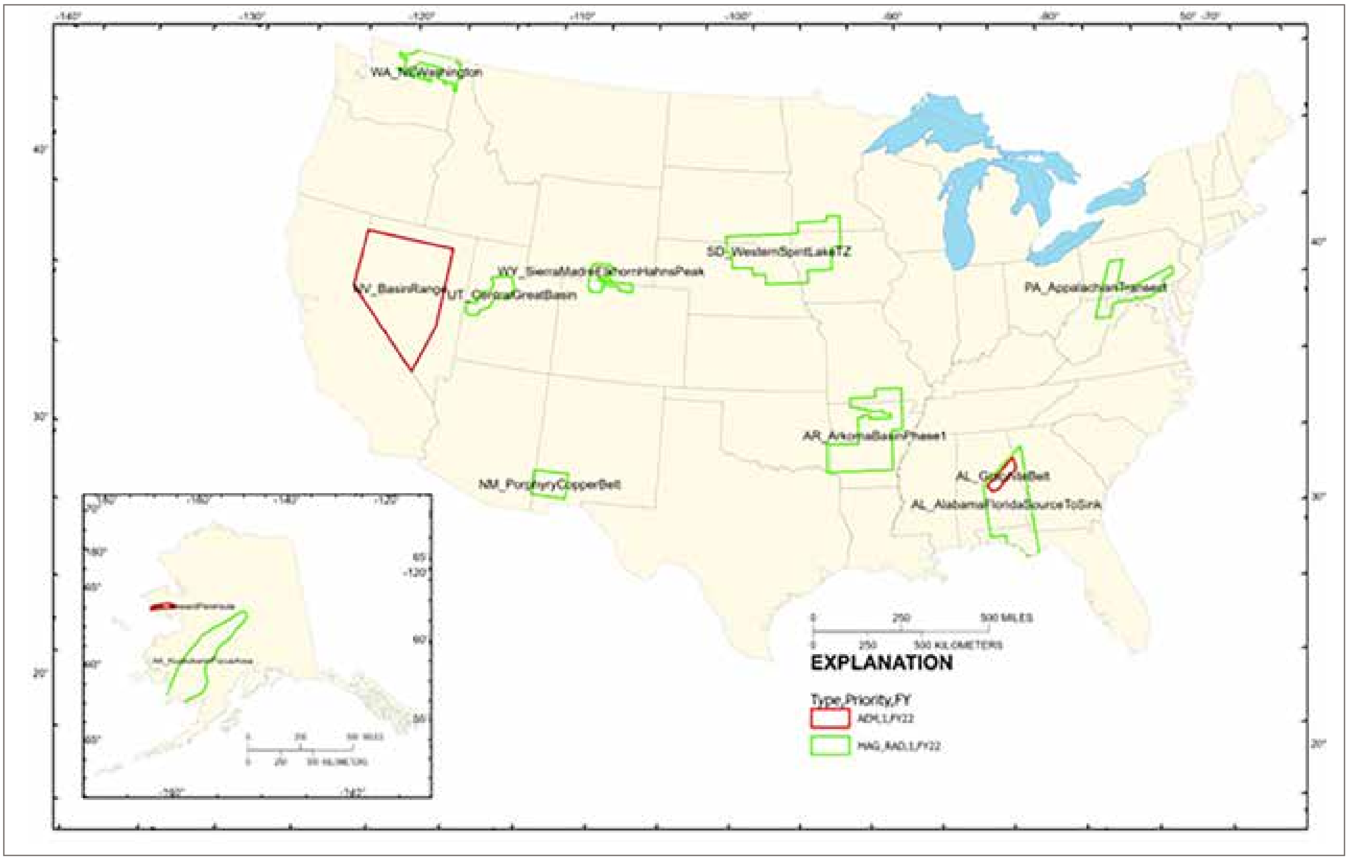
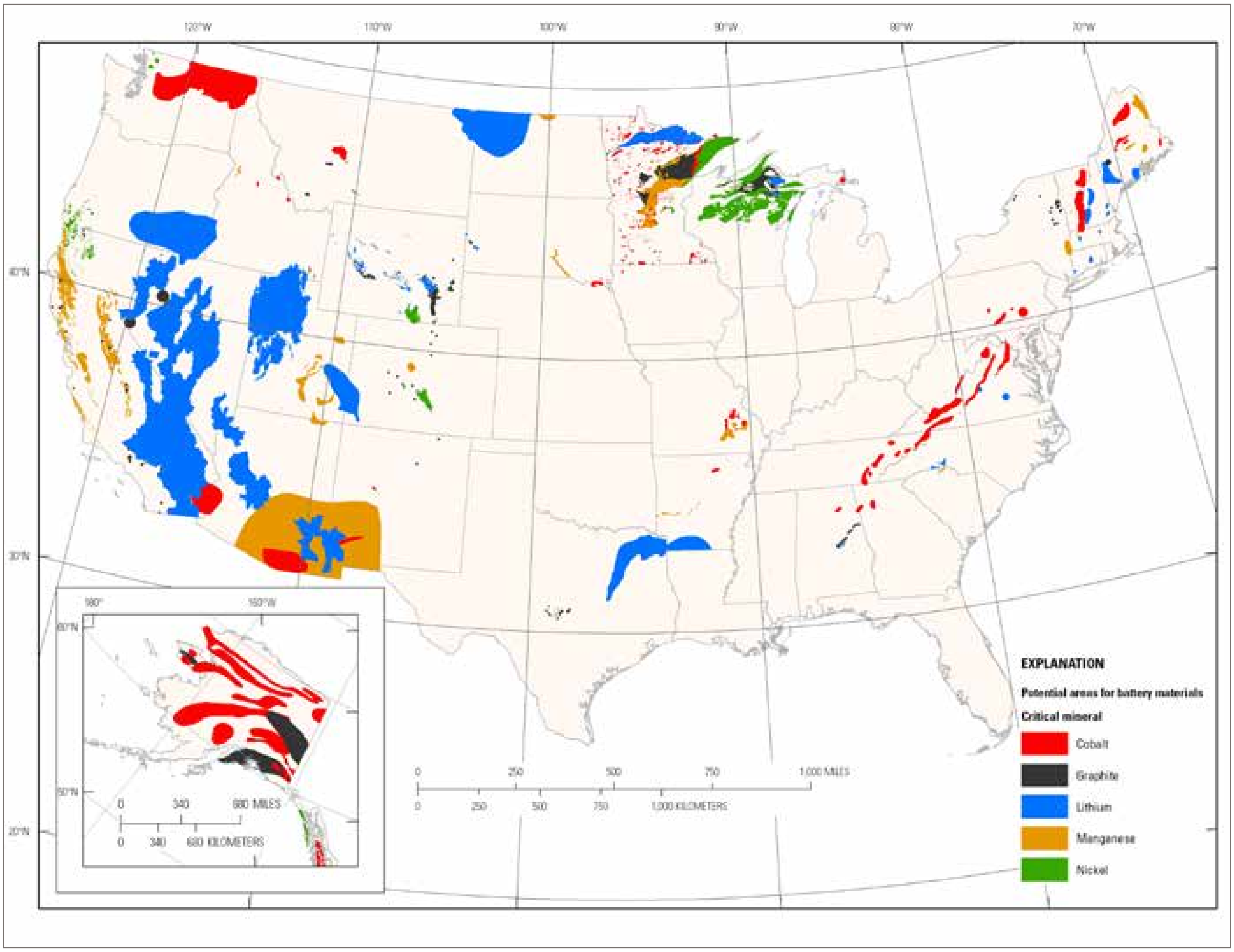


Figure 5

Areas in the United States that are favorable for hosting mineral systems that commonly contain critical minerals used in the manufacturing of lithium-ion batteries.



data-driven modelling effort utilizing baseline geologic and geophysical data was recently completed, outlining regions prospective for Mississippi Valley Type and clastic sediment deposits (Lawley et al., 2022). An example of the output from the modelling efforts is shown in Fig. 3. In addition, a knowledge-driven modelling approach, using criteria updated from Emsbo (2009) is in progress.

The CMMI collaboration has several ongoing activities. Evaluation of existing geochemical data in the global database with respect to critical minerals in different deposit types is underway. CMMI has designed this effort to identify gaps in the existing database that can lead to additional data collection. The USGS is currently leading the effort to organize and publish national-scale geologic, geophysical and mineral resource data layers and related derivative products for each member country. These data can be used in the upcoming knowledge-driven modelling efforts and in a new effort to link the tectonic evolution and paleoenvironment to the formation of sediment-hosted basin deposits. More broadly, CMMI generated geologic, geophysical, geochemical and paleo-tectonic data that are intended to provide the foundational framework to underpin a robust understanding of critical mineral endowment in a broad range of system types across the member nations and globally.

Domestic critical mineral resources: Earth Mapping Resources Initiative (Earth MRI)

The USGS Earth MRI was established in FY 2019. Its primary goal is to acquire modern geoscience data to support the nation's need for basic geologic, geophysical, geochemical and topographic data to characterize areas

Figure 6

A map showing sites with >1,000 tons of historic graphite production or contained graphite resource.

that have potential for hosting critical mineral resources. "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals," (U.S. Department of Commerce, 2019) issued in response to EO 13817, and Title VII of the Energy Act of 2020 direct the USGS to carry out comprehensive national assessments of identified and undiscovered resources of critical minerals. The initial funding for Earth MRI was approximately $9.6 million in FY 2019 and was increased in FY 2020 to $10.6 million. As noted above, the Bipartisan Infrastructure Law provides a significant increase in annual funding for five years beginning in FY 2022.

In 2021, Earth MRI launched 14 new geologic mapping projects and two regional geochemical reconnaissance projects. Examples include new mapping projects in the Westminster Terrane in Maryland, heavy mineral placer areas in the Atlantic Coastal Plain of North and South Carolina and the Fall Zone in Virginia, the Alabama graphite-vanadium belt, the Idaho cobalt belt, the Upper Mississippi Valley mineral belt in Wisconsin, the Salton Sea area in California, and the Yukon-Tanana Uplands in Alaska. A full description and access to all Earth MRI geologic, geochemical, geophysical and lidar projects is available online (Earth MRI, 2022).

The USGS Earth MRI project team is collaborating with the Department of Energy Geothermal Technologies Office to collect a large regional aeromagnetic and radiometric survey and accompanying lidar for the Walker Lane area of western Nevada. This region is not only highly prospective for lithium and other critical minerals, but also for geothermal resources (GEODAWN, 2020). A similar partnership with DOE is carrying out integrated geologic mapping, lidar, and airborne geophysics over the Salton Sea region of southern California to characterize areas containing known geothermal and lithium resources (Geoflight, 2021). These projects are enhanced through partnerships with other federal agencies, such as the U.S. Bureau of Land Management, and the respective state geological surveys.

The FY 2021 Earth MRI geochemical reconnaissance projects include the continuation of the effort to examine the REE endowment of Devonian phosphatic rocks across a multistate region of the central U.S. and the launch of an evaluation of the REE potential of Ordovician phosphatic rocks in Iowa and Indiana. All geochemical data generated by projects funded by the USGS Earth Mapping Resources Initiative are updated quarterly (U.S. Geological Survey, 2021). To date, the geochemical database includes more than 6,000 samples of rock and sediment from 23 states.

Nine large high-resolution airborne magnetic and radiometric surveys and three airborne electromagnetic surveys are being designed and are anticipated to be under contract in FY 2022 or early FY 2023. These surveys are intended to complement geologic mapping and mineral resource research and optimize coverage of important geologic features throughout the country (Fig. 4). The airborne electromagnetic surveys are focused on areas permissive for hosting graphite in Alaska and Alabama and complement other airborne geophysical data and geologic mapping in the critical mineral-bearing regions in the Great Basin in Nevada.

Project phases 1 and 2 considered rare earth minerals and critical minerals that mainly occur as primary commodities - aluminum, cobalt, graphite, lithium, niobium-tantalum, platinum-group elements, tin, titanium and tungsten. In partnership with representatives of 38 state geological surveys, the USGS completed Phase 3 of the Earth MRI project, which defined broad focus areas for mineral systems throughout the United States. Focus areas are classified by mineral systems, deposit types, and known and potential critical mineral commodities. The mineral systems classification developed for Earth MRI documents the relationship between large mineral systems that may contain multiple deposit types and the mineral commodities associated with each deposit type (Hofstra and Kreiner, 2020). Many focus areas have evidence of multiple overlapping mineral systems and deposit types that warrant new data acquisition to evaluate critical mineral potential. Phase 3 considered mineral systems and deposit types for 13 critical mineral commodities: antimony, barite, beryllium, chromium, fluorspar, hafnium, helium, magnesium, manganese, potash, uranium, vanadium and zirconium. Results are published as a geographic information system (GIS) of focus areas and data tables that explain the rationale for each focus area, along with information about critical mineral occurrences, historical mining, recent exploration, existing geologic maps and other data and references (Dicken et al., 2021). Summary reports that accompany these data releases discuss the mineral systems and deposit types for these 13 critical minerals in the conterminous United States (Hammarstrom et al., in press) and Alaska (Kreiner and Jones, in press). An example of the types of information in the summary reports is shown in Fig. 5, which outlines areas with potential for hosting mineral systems that commonly contain the metals necessary to manufacture batteries (cobalt, graphite, lithium, and manganese) used in electric vehicles

Active mining and exploration projects for heavy-mineral sands along the Atlantic Coastal Plain target zircon, titanium minerals, and in some cases the rare-earth mineral monazite, which can be recovered as a byproduct. To help better characterize the placer deposits in this region, the USGS published the first publicly available, high-resolution aeroradiometric survey over the U.S. Atlantic Coastal Plain, which contributes to our understanding of the potential for placer deposits to host titanium and zirconium (Shah, 2020; Shah et al., 2021). Aeroradiometric surveys can directly image heavy mineral sand concentrations that contain monazite to target prospective areas for drilling.

Domestic critical mineral resources: Mineral resource assessments

The USGS is addressing the mandate in the Energy Act of 2020 to carry out comprehensive national assessments of identified and undiscovered resources of critical minerals. One such example is tungsten, which has important applications in the aerospace, defense, energy, telecommunications and other industries where it is used in cemented carbides as wear-resistant materials for metalworking, mining and construction. It ranked 20th out of the 50 mineral commodities evaluated for the 2022 U.S. critical minerals list (Nassar and Fortier, 2021). No tungsten is currently mined domestically, and China is the top global producer and supplier of tungsten to the United States. The USGS Mineral Resources Program has completed mineral resource assessments of tungsten skarn deposits in the Yukon-Tanana Uplands of Eastern Alaska (Case et al., 2021, 2022a), the Northern Rocky Mountains of Montana and Idaho (Goldman et al., 2022), and the Great Basin region of western Nevada and eastern California (Lederer et al., 2020, 2021). Historically productive areas in the Great Basin are estimated to contain significant undiscovered tungsten skarn resources with median in-place undiscovered resources of 940 kt (1.1 million st) of WO_3. This estimate represents more than five times the identified tungsten resources (168 kt or 185,000 st WO_3) from past production and remaining in-place resources in that region. The Great Basin assessment area covers 44,000 km^2 in Nevada and California, broken up into five geologically distinct domains that range in size from about 5,000 to 13,000 km^2. Individual domains within the Great Basin are comparable in size to areas assessed in Idaho and Montana in the Northern Rocky Mountains (7,600 km^2) and in the western Yukon-Tanana area of Alaska (9,200 km^2). Median in-place undiscovered tungsten resources in these smaller areas are 200 (220 st) and 94 kt (1.1 million st) of WO_3, respectively.

Mafic magmatic mineral systems host deposits of platinum-group elements, chromium, nickel and cobalt. In the United States, the Stillwater Complex in Montana and the Duluth Complex in Minnesota are important examples of intrusions that host these deposit types. As part of a systematic effort to provide objective descriptive information about the rocks that host these deposits, the USGS published a series of data releases that document thin section images for drill core and rock samples. Additional data releases that can help to inform planned mineral resource assessments include new drill core logs prepared by the USGS and collaborators on core drilled by mineral exploration companies from the Stillwater Complex (Parks and Zientek, 2020; Howard et al., 2020; 2021a,b). Moreover, field, laboratory, and modelling studies on the Stillwater Complex, the nation's major producer of platinum and potential chromium resource, explain how these types of deposit form and why they are likely restricted to Archean and Proterozoic layered intrusions (Jenkins et al., 2020, 2021).

In 2019, a targeted scientific study began on the Graphite Creek flake graphite deposit, Seward Peninsula, Alaska, to update models of graphite genesis for use in assessments (Case et al., 2022b). The findings of this research can help to inform a national graphite assessment initiated by USGS in 2021.

Domestic critical mineral resources: USMIN

The USGS, through the USMIN mineral deposit database project, publishes comprehensive 21st century geospatial databases that are the most authoritative source of information about important mines and mineral deposits in the United States and its territories. These databases provide high-quality data to inform land management decisions and policies, deliver digital data for integration with other data sources and make digital data and metadata freely available to stakeholders on the USMIN website (U.S. Geological Survey, 2022b). ArcGIS users can access all USMIN databases by searching ArcGIS online for USMIN (ArcGIS Online, 2022).

USMIN has published databases that document the known production and resources for significant critical mineral deposits in the United States for 25 of the 50 minerals included on the federal critical minerals list (Federal Register, 2022): cobalt, gallium, germanium, graphite, lithium, niobium, tantalum, tellurium, tin, tungsten and rare earth elements, which include cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, samarium, terbium, thulium, ytterbium and yttrium (Burger et al., 2018; Karl et al., 2018; Bellora et al., 2019; Karl and Mauk, 2019; Karl et al., 2019; Gnesda et al., 2020; Karl et al., 2020; Karl et al., 2021a,b,c; Karl et al., 2022).

USMIN's utility was recently demonstrated through a published data release on graphite (Karl et al., 2022). These data provide information on 10 U.S. sites that have a contained resource and (or) past production of more than 1 kt (1,100 st) of graphite, which is approximately 2 percent of the average annual U.S. consumption of graphite in the United States from 2017 through 2021. Sites in this dataset occur in Alaska, Alabama, Colorado, Montana, New York, Pennsylvania and Texas (Fig. 6). Graphite is the dominant anode material in lithium-ion batteries because it is a relatively low cost and abundant material that provides high energy density, power density, and a very long charge/discharge cycle life (Zhang et al., 2021). The International Energy Agency (2021) estimated that a concerted effort to reach the goals of the 2015 Paris Agreement would require 25 times more graphite in 2040 compared to 2020, principally for batteries for electric vehicles and energy storage.

In 2021, the United States was 100 percent net import reliant on graphite from countries that included China, Mexico, Canada, and India (U.S. Geological Survey, 2022a). Graphite has not been produced in the United States since the 1950s, and the USGS estimates that China produced 79 percent of the world's graphite in 2021. The lack of U.S. production and projected demand growth have underscored the criticality of graphite. Most of the graphite deposits in the USMIN database contain flake graphite. These occur in metamorphic belts: the Appalachians in the eastern United States, the Llano Uplift in Texas, and metamorphic rocks in Colorado and Alaska. These deposits, combined with other known occurrences that are not shown in Fig. 6, help to define areas that may be favorable for future graphite exploration.

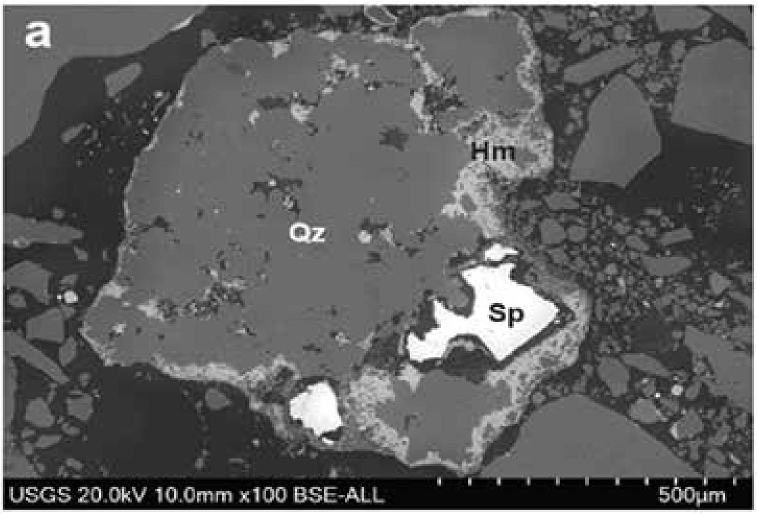
On a global basis, most currently mined flake graphite deposits contain at least 8 to 12 percent graphitic carbon in deposits larger than 500 kt (550,000 st) (Robinson et al., 2018). The largest deposit in the United States is the Graphite Creek deposit in Alaska, with measured, indicated, and inferred resources of more than 100 Mt (110 million st) containing approximately 8 percent graphite for a total of more than 8 Mt (8.8 million st) of graphite (King et al., 2019). This deposit is undergoing active exploration, and if brought into production, could make a substantial contribution to the approximately 44 kt (48,500 st) of graphite that was consumed in the United States, on average, for each of the last five years (2017-2021) (U.S. Geological Survey, 2022a).

Critical mineral research

The USGS is expanding efforts to evaluate and assess sources of critical minerals (and other commodities) to include the mine waste at abandoned mines. Research at the Tristate lead-zinc district, Oklahoma, has been investigating the occurrence of germanium (Ge) in the mine waste piles locally known as “chat” (White et al., 2020). This work additionally sheds light into the complexities of ore-forming conditions related to germanium precipitation. Germanium, which is an important critical mineral used as a dopant in fiber optic cables also has uses in semiconductors and in infrared optical devices with a variety of military and industrial applications (Shanks et al., 2017). Although the Tristate district was mined for lead and zinc (as galena and sphalerite), the sphalerite also hosted significant amounts of germanium, which was produced as a byproduct. In fact, the Tristate district is where germanium metallurgical techniques were initially developed with the first germanium dioxide produced in 1941 from flue dusts derived from sphalerite smelting (Fite, 1954).

Figure 7

Germanium in chat in the Tristate district, Oklahoma. a. Back-scattered electron scanning electron microscope (SEM) image of chat showing a quartz clast (dark gray) and sphalerite grain (white) surrounded by a secondary rim of hemimorphite (light gray).



Electron microprobe analyses of samples from the Tar Creek Superfund site reveal document concentrations up to 750 mg/kg Ge in the sphalerite (White et al., 2020). Electron microprobe analyses coupled with X-ray spectroscopy reveal complex substitutional mechanisms for Ge in sphalerite that should reflect ore-forming conditions conducive to germanium precipitation. Germanium was found in both the Ge^{4+} and the Ge^{2+} oxidation states, which suggest that the oxidation state of the hydrothermal fluid may play an important role in both the transport and precipitation of germanium. Germanium concentrations in sphalerite also show a strong correlation with copper, indicating a coupled substitution, which adds additional complexity to depositional mechanisms.

Whereas the sphalerite ore was the original host of the germanium, the weathering behavior of germanium in the chat piles has implications for potential extraction and recovery from the mine waste (White et al., 2020). The chat piles include gravelly waste from historical crushing of ore when gravity separation was the primary ore-processing technique, to which modern flotation tailings were subsequently applied. The Tristate district is somewhat atypical for Mississippi Valley-type deposits in the significant amount of silicic alteration that was associated with mineralization. Weathering of the chat produces the hydrous zinc silicate mineral hemimorphite $[Zn_4Si_2O_7(OH)_2 \bullet H_2O]$ as a weathering product (Fig. 7).

Detailed electron microprobe analyses document concentrations of Ge in sphalerite ranging from < 90 to 750 mg/kg, whereas the Ge concentration in hemimorphite is significantly higher, up to 2,200 mg/kg (White et al., 2020). Hence, any attempts to recover germanium by targeting the sphalerite during reprocessing of the chat may will miss that which is hosted by hemimorphite.

The USGS is also taking a broader approach to investigate the resource potential of mining waste. The number of abandoned hardrock mine features on federal lands is estimated to exceed 140,000, and the estimated costs to address the environmental and physical hazards at these abandoned mine sites are daunting (U.S. Government Accounting Office, 2020). The USGS, in cooperation with the National Park Service and the Department of Interior Office of Environmental Policy and Compliance, is conducting research to evaluate the resource potential of mine waste to explore the possibility of offsetting the remediation costs by simultaneously recovering valuable commodities. The USGS has established an agreement with the National Park Service to evaluate the resource potential and environmental risks of mill tailings at the abandoned Katherine gold-silver mine in the Lake Mead National Recreation Area, Arizona, as one example.

Conclusion

The USGS has been a leader on critical mineral issues for several decades, contributing, in many ways, to the current level of visibility and understanding of an important societal issue (Brobst and Pratt, 1973; Schulz et al., 2017). Mineral information, mineral resource assessments, mapping and surveying, and mineral research are all core competencies of the Bureau. USGS mineral information underpins the methodology for the evaluation of critical mineral supply chain risks and the development of the U.S. critical minerals list. USGS mineral resource assessments, mapping and surveying efforts are essential for understanding domestic mineral prospectivity for new sources of critical minerals, including those in unconventional sources such as mining wastes. Identifying risks to supply chains and new sources of critical minerals prompts questions to be addressed by USGS research regarding the mineralogical distribution of critical elements to understand potential extractive mechanisms.

In an era characterized by a global pandemic, tense trade relationships, natural disasters, and, most recently, large scale military conflict in Europe, the strain on global supply chains has become painfully obvious. All this is occurring as a backdrop to an industrial revolution scale transformation of the global energy sector requiring huge quantities of mineral resources (World Bank, 2020), the bulk of which are still in the ground. The need for fact-based, objective analysis and research on mineral resources, and their supply, demand, and consumption has perhaps never been greater. The transition from vehicles powered by internal combustion engines to electric motors, in particular, represents the nexus between transportation, energy, and technology (Muratori et al., 2021), three major sectors of the 21st century global economy. The U.S. Government has embraced a "whole of government" approach to addressing supply chain vulnerabilities (White House, 2021) signaling a clear appreciation of the challenges facing the Nation in this sphere. The USGS Mineral Resources Program has and will continue to deliver its mission in service to the Nation, in collaboration with academic, government, industry, tribal, and public stakeholders. ■

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