

USGS critical minerals review

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The United States Geological Survey (USGS) provides scientific information for the Department of Interior and the nation, consistent with its original mission expressed in the Organic Act of 1879 (43 U.S.C. 31): “the classification of the public lands and examination of the geological structure, mineral resources, and products of the national domain.” Recent legislation such as the Infrastructure Investment and Jobs Act (43 USC 311) and executive actions (Executive Orders 14154, 14153, 14241 Secretarial Orders 3417, 3418, 3422) continue to focus the mission on critical mineral resources.

The 2022 Final List of Critical Minerals includes 50 commodities (U.S. Geological Survey, 2022a); the list is supported by a published, peer-reviewed methodology (Nassar and Fortier, 2021; Nassar et al., 2020), and is subject to revision on a three-year cycle according to the Energy Act of 2020 (30 U.S.C. 1606). The Infrastructure Investment and Jobs Act (43 USC 311) directed the USGS Mineral Resources Program and its 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 domestic critical mineral resources in surface or subsurface deposits and prioritizes mapping and critical mineral assessments. Earth MRI activities support 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 2024. Contributions describe new directions in critical mineral supply chains, international collaboration and partnerships, innovations in mineral resource assessment methods, new data collection activities initiated under Earth MRI, emerging outcomes from Earth MRI geophysical surveys, and developments in critical mineral characterization in mine waste. It is impractical to highlight all the relevant work being conducted by the USGS in this area, so these selected contributions are intended to convey the

depth and breadth of research activity on critical mineral priorities and partnerships in the United States.

Critical mineral supply chains

Modern technology depends on reliable supplies of mineral commodities. Yet, their supply chains are under increasing strain from regional conflicts, trade disputes and resource nationalization. The pressures affecting global mineral commodity supply chains are coming at a time of unprecedented growth in demand, rising adoption of new technologies, and advances in aerospace and defense systems. Assessing these risks is a priority for import-dependent countries, with many countries developing lists that highlight the commodities of most concern to them (Nassar et al., 2024).

Researchers at the USGS have expanded upon existing methodologies and have developed a new model that assesses the economic effects of mineral commodity disruptions on the U.S. economy. Using the input-output (IO) framework (Leontief, 1951) and linear programming methods, Manley et al. (2022) extended work by Levine and Yabroff (1975) to assess the effects of mineral commodity supply disruptions on industries, sectors and the overall U.S. economy. The USGS has further developed this methodology by estimating price elasticities for demand and supply for several mineral commodities to determine a new, post-disruption, market equilibrium. From this, it is possible to quantitatively estimate the economic effects of a mineral commodity supply disruption on U.S. industrial output and overall economic activity.

The USGS incorporated a second enhancement by recognizing that an entire industry’s output may utilize a material only in certain cases. For instance, whereas copper is used in virtually all electronics manufacturing, only a specialized subset of applications utilizes gallium and germanium in their manufacturing processes (Nassar et al., 2024). A third major advancement involved changing the model’s objective function, which resulted in a nonlinear optimization problem. Nonlinear optimization more closely approximates real-world systems by capturing complex dependencies that exist between model variables. In this way, nonlinear

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

Figure 1

Effects of various net export restrictions on the price and quantity of gallium and germanium (from Nassar et al., 2024).

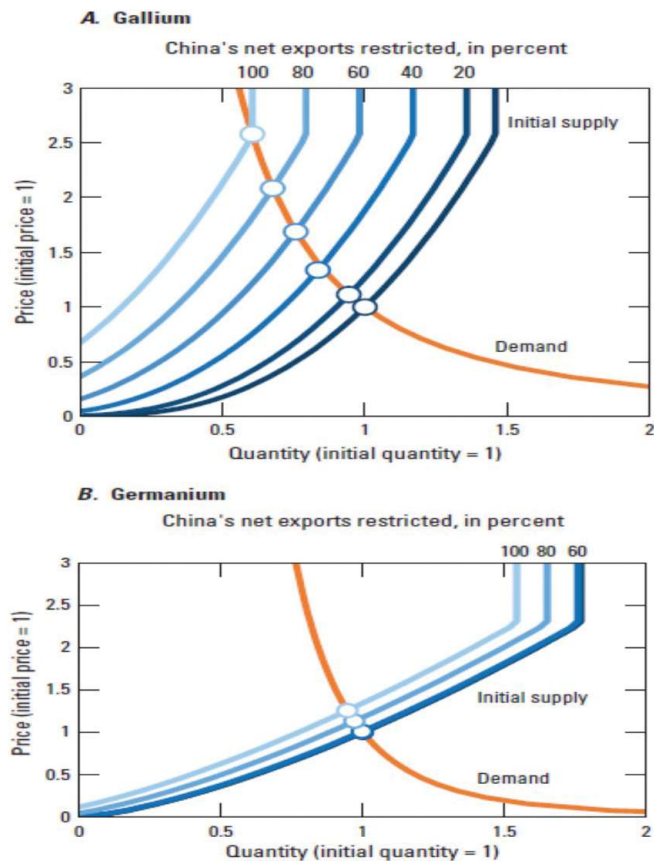
optimization comes closer to optimal modeling solutions compared to linear models.

In 2023, the government of the People's Republic of China (PRC) imposed trade restrictions on exports of gallium, germanium, antimony and graphite (Ministry of Commerce and General Administration of Customs [China], 2023). Then, in December 2024, the PRC implemented an embargo on gallium, germanium and antimony exports to the United States and tightened restrictions on graphite (Baskaran and Schwartz, 2024). A few months earlier, in October 2024, the USGS published a paper assessing the potential economic effects of China's export ban on gallium and germanium (Nassar et al., 2024).

Gallium and germanium supply disruption.

Production concentration is the primary factor contributing to a material's susceptibility to disruption. Since 2014, China has produced more than 90 percent of global primary gallium (Jaskula, 2025; U.S. Geological Survey, 2024e). China is also a major producer of primary germanium, and other producers include Canada, Belgium and Russia (Tolcin, 2025; U.S. Geological Survey, 2025e). Primary germanium produced in Canada comes from U.S. zinc concentrate from the Red Dog Mine in northwestern Alaska that is shipped to Teck in British Columbia for refining (Tolcin, 2025). As of 2023, U.S. net import reliance for primary gallium was 100 percent while the net import reliance for primary germanium was greater than 50 percent (U.S. Geological Survey, 2025e). Another complicating factor related to gallium and germanium is that their primary production is as a byproduct from bauxite and zinc, respectively, which suggests their supply may be price inelastic (Graedel et al., 2015).

Gallium and germanium are used in certain compound semiconductor devices including light-emitting diodes (LEDs), photonics and photovoltaic (PV) cells. These two mineral commodities' superior electron mobility allows faster switching speeds while their excellent thermal conductivity permits devices to dissipate heat more efficiently. Demand for these mineral commodities is growing rapidly to meet growth in power electronics, light-emitting diodes, integrated circuits, 5G networks, solar power and fiber optics, among other applications (Project Blue, 2024). Finally, the markets for gallium and germanium are small and data on their production, consumption, trade and pricing are difficult to obtain. All these factors make an assessment of gallium and germanium vital, challenging and full of uncertainty.



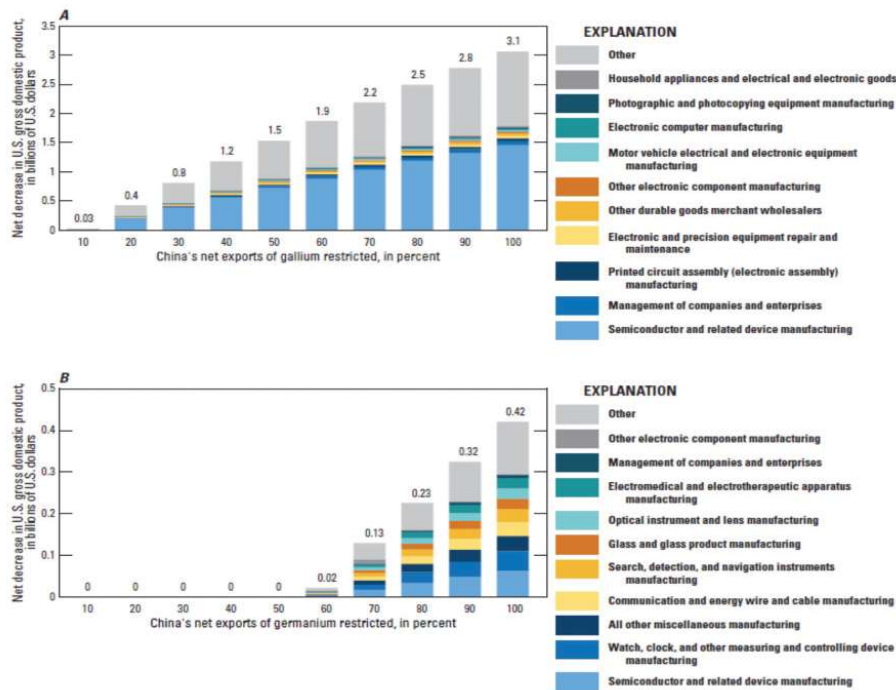
As mentioned briefly above, the USGS model utilizes price elasticities and the IO framework to first estimate a new market equilibrium at various levels of China's net export restrictions for gallium and germanium and, secondly, to assess the impact of these restrictions on U.S. industrial output and gross domestic product (GDP). In the 'base case' model, USGS set China's net export restrictions in a range of 10 to 100 percent for both gallium and germanium. The consumption of imports was offset by release from national stockpiles. This ultimately led to a predicted net export restriction ranging from 60 to 100 percent for germanium (Nassar et al., 2024). Given the respective price elasticities of supply and demand for gallium and germanium, the authors were able to estimate a new market equilibrium for each level of supply disruption.

The model predicts a complete one-year restriction of China's net exports of gallium to the rest of the world, estimated to be 159 t (175 st) out of a total world production of 638 t (703 st) in 2022 (Nassar et al., 2024), would cause gallium prices to increase 2.5-fold while

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Figure 2

Estimated net decrease in U.S. gross domestic product at different levels of restrictions of China's net exports of (A) gallium or (B) germanium, by industry (from Nassar et al., 2024).



the quantity of gallium available to the rest of the world would decrease by about 40 percent (Fig. 1). The effects on germanium (Fig. 1) are similar but not as extreme. Specifically, the model predicts a complete restriction of China's net exports of germanium lasting one year would cause prices to rise by about 26 percent while the quantity available to the rest of the world would decrease by about 5.5 percent (Nassar et al., 2024).

The contrast in the effects of a complete restriction of China's net exports of gallium and germanium are observable through their respective elasticities. Both markets can be characterized as price inelastic as the absolute value of their price elasticities of demand and supply were between zero and one. The supply of germanium exhibits greater price elasticity compared to gallium, whereas the price elasticity of demand for germanium was lower in absolute terms than that for gallium (Nassar et al., 2024). Notably, a complete restriction of China's net exports of germanium had a lower effect than that of gallium due to differences in elasticities and, importantly, the higher levels of germanium production, capacity and strategic inventories in the rest of the world. The modeling restrictions on China's net exports of germanium started at 60 percent because restrictions up to 58 percent could be offset by available strategic inventories, thereby resulting in no shift in the supply curve

(Nassar et al., 2024).

Turning to the IO framework, the authors utilized the new equilibrium prices and quantities to assess the impact of China's complete net export restriction of gallium and germanium on individual U.S. industries and overall U.S. GDP. The model predicts a complete net export restriction of gallium would result in an estimated \$3.1 billion reduction in U.S. GDP if the restriction were to last one year (Fig. 2). Nearly half (46.5 percent) of the reduction was predicted to be in the semiconductor and related device manufacturing sector — the industry to which gallium consumption was directly linked in the model (Nassar et al., 2024). The remainder of the decrease was spread

among various other downstream industries that consumed gallium indirectly.

The predicted decrease in U.S. GDP associated with a one-year complete net export restriction of germanium was \$420 million. This was mainly due to the lower reduction in quantity and increase in price of germanium compared to that of gallium. In contrast to gallium's impact on the U.S. economy, the effects of the germanium restriction were predicted to be spread more evenly throughout the 11 industrial sectors affected. The main reason for this is that, while these sectors are directly connected to germanium consumption, they were not large consumers of germanium (Nassar et al., 2024). In some cases, the industries that contributed the most to the overall decline in U.S. GDP were not themselves predicted to be most affected by the disruption. That is because these sectors contribute relatively more to U.S. GDP than the sectors that were more affected by the disruption (Nassar et al., 2024).

The assessments summarized above present a case study in the usefulness of economic analysis to enhance and deepen our understanding of the potential impact of supply disruptions on U.S. industrial output and overall GDP. By estimating price and quantity effects with elasticities and incorporating the new market equilibrium into an IO framework, one can begin to determine how supply disruptions may impact U.S.

economic activity. This and similar analyses can inform a variety of private-sector strategies and government policies to counteract the effects of supply disruptions. Supply-chain diversification, partnering with allies and friendly nations, domestic capacity building and the increased use of recycling are some examples of potential actions that stakeholders could take to mitigate the effects of supply disruptions.

Estimating price elasticities of demand for lithium-ion battery materials. Price elasticity can also help inform how end-users respond to price changes. A recent USGS paper, “Estimating price elasticity of demand for mineral commodities used in lithium-ion batteries in the face of surging demand” (Shojaeddini et al., 2024), empirically estimated the price elasticity of demand (PED) for cobalt, graphite, lithium, manganese and nickel to determine how accelerating adoption for electric vehicles (EVs) has influenced each of these markets. The paper also examined the role of “structural breaks” to determine if PEDs have changed due to shifts in the end-uses for battery materials. A structural break in a time series refers to a sudden or significant change in the underlying pattern or statistical properties of the data at a specific point in time, meaning the relationships between the variables in the series change abruptly, often signifying a shift in the underlying economic or social system causing the data. Statistical tests can assess if the time series returns to its original pattern (stationary) or embarks on a new trend (nonstationary) following the structural break. These tests indicate that several battery materials exhibited nonstationary behavior following the structural breaks. Specifically, lithium, cobalt, nickel and manganese became less demand elastic following structural breaks in 2020, 2013, 2009 and 2014, respectively (Shojaeddini et al., 2024). The structural break years represent an average break time and may not necessarily align with a specific major event in the market as these breaks can result from multiple influencing events occurring over several years.

The global energy transition has led to a rapid increase in the demand for the mineral commodities used in batteries. For example, consumption of cobalt in lithium-ion batteries has increased by 189 percent over the years 2008 to 2021 (Shojaeddini et al., 2024) with batteries now accounting for more than half of total global cobalt demand. A greater understanding of the PED can help provide policymakers and industry stakeholders with valuable insights into how changes in mineral commodity prices impact consumer demand (Shojaeddini et al., 2024).

Specifically, as the demand for lithium, cobalt, nickel and manganese have become more price inelastic following their respective structural breaks, substitution becomes more of a challenge. This may be addressed by exploring long-term supply sustainability, supply-chain diversification, increased use of recycled material and optimal resource allocation, for example (Shojaeddini et al., 2024).

Comparing the results of Shojaeddini et al. (2024) to other research is challenging due to the lack of previous studies for lithium and graphite (Shojaeddini et al., 2024) while PED studies for cobalt and manganese date from 1985. However, in the case of cobalt, there have been shifts away from its use in superalloys, hard metal and magnets amid a growing market share for lithium-ion batteries. Manganese demand has also undergone structural changes, but consumption is still dominated by steel. As mentioned earlier, as the demand for battery materials has become more price inelastic, end-users have less flexibility to modify their consumption when confronted with supply shocks. This can lead to higher prices that could ultimately affect final consumers (Shojaeddini et al., 2024).

While PED analysis can inform strategies geared toward supply sustainability, caution is urged on relying exclusively on historical data to estimate future market behavior, including those behaviors related to price shocks. Markets may undergo fundamental transformations due to disruptive technological change, changes in consumer preferences and government policies (Shojaeddini et al., 2024). These factors can influence the accuracy of predicting future PEDs using historical trends.

International minerals collaboration

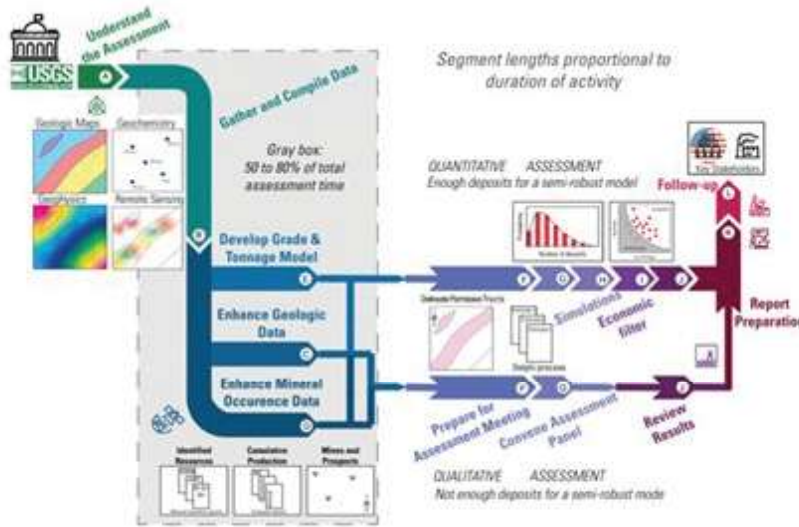
The USGS continues to cooperate with international partners in the field of geology and natural resources. Past and present engagements aim at enhancing the understanding and management of critical minerals and to mitigate strategic mineral resources vulnerabilities. For example, the USGS continues to partner with Geoscience Australia and the Geological Survey of Canada to collaborate as part of the Critical Minerals Mapping Initiative (CMMI).

A sample of the recent activities carried out by USGS scientists in other countries include the completion of a quantitative assessment of tungsten skarn and qualitative assessments of rare earth elements (REEs), graphite, uranium and gold in two mountain ranges in Uzbekistan (Coyan et al., 2024), evaluations of REE resources in Botswana, bauxites in

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Figure 3

Schematic workflow of a typical mineral resource assessment (DARPA, 2023).



the Dominican Republic, lithium in brines in the “lithium triangle” of Chile, Argentina and Bolivia, as well as new engagements starting in the year 2025 with Kazakhstan and Angola. In all cases, these cooperative work efforts have included the provision of training colleagues on various field and office techniques, such as geophysics, geochemistry, remote sensing and methodologies for the assessment of unknown mineral resources, particularly of critical commodities. New interests have risen on the recovery of minerals from mine waste, as well as on conventional and unconventional energy resources. These exchanges of knowledge and technology contribute to the enhancement of the USGS understanding of local to global mineral deposit models and the deployment and testing of known and in-development tools for mineral prospectivity mapping, including modern ones that involve the use of artificial intelligence and machine learning (AI/ML).

Critical Mineral Assessment with AI-Support (CriticalMAAS)

Earth MRI in partnership with the Defense Advanced Research Projects Agency (DARPA) and Advanced Research Projects Agency—Energy (ARPA-E) kicked off a collaborative program in August 2023 that concluded in February 2025 (DARPA, 2023). The 18-month program aimed to increase the efficiency of conducting a mineral resource assessment by several orders of magnitude through automation of key time-consuming steps in mineral resource assessment workflows (Fig. 3). The program was organized around four technical areas, including (1) extracting information from maps, (2) compiling information on mineral occurrences

from reports and databases, (3) developing predictive models for mineral prospectivity using publicly available geoscientific data and (4) designing human machine interfaces for utilizing advanced machine learning tools through interfaces with minimal coding required from users and linked to a data repository.

The outcomes of the CriticalMAAS program are immediately tangible and available to USGS mineral resource assessment practitioners. Training users and populating the repository with Earth MRI, and other modern high-quality geochemical, geophysical and geological data sets, both remain a priority for

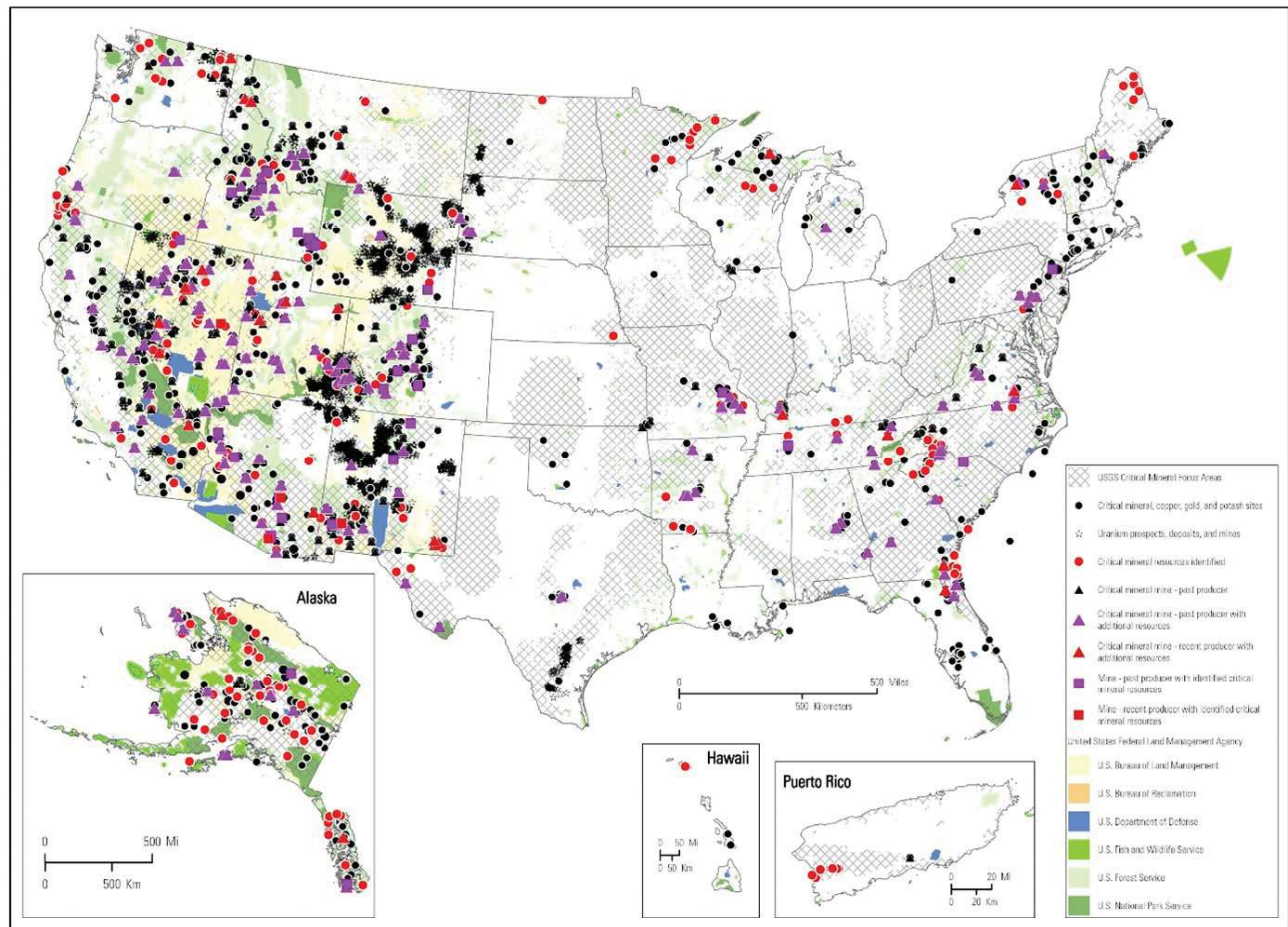
conducting mineral resource assessments for critical minerals in the United States. The predictive analytical power combined with new data acquisition partnerships with state surveys and careful, rigorous peer review by experts in mineral deposit systems continue to be a focus of USGS science.

Earth MRI

The USGS launched Earth MRI in 2019 under the mandate of Executive Order 13817 to improve our knowledge of the geologic framework of the United States and to identify new domestic sources of critical mineral resources. Earth MRI was established as a long-term, multiyear effort with new, sustained funding from Congress, and it was built as a partnership between the USGS and state geological surveys as well as other federal, state, tribal and private-sector organizations. The close cooperation between federal and state geologists has been a hallmark of this initiative and key to its accomplishments. Earth MRI is a data collection engine, acquiring new high-resolution geophysical, geologic and topographic (elevation) data across the entire nation with an emphasis on priority regions, or “focus areas,” that have known or suspected critical mineral resource potential. In 2021, supplemental funding through the Infrastructure Investment and Jobs Act significantly accelerated and expanded collection of these fundamental geoscience data sets, broadened Earth MRI’s scope to include evaluation of above-ground resources and mine waste, and provided new opportunities for data integration and analysis. Through its first six years, Earth MRI has vastly improved the geoscience data landscape for many regions

Figure 4

Map showing critical mineral-bearing deposits in the United States and Puerto Rico and Earth MRI focus areas (data from Hammarstrom et al., 2023a; Dicken et al., 2022).



of the United States, transformed the nation's evidence base for resource management, fostered discovery of new critical mineral resources and spurred new partnerships and investments across our growing stakeholder base.

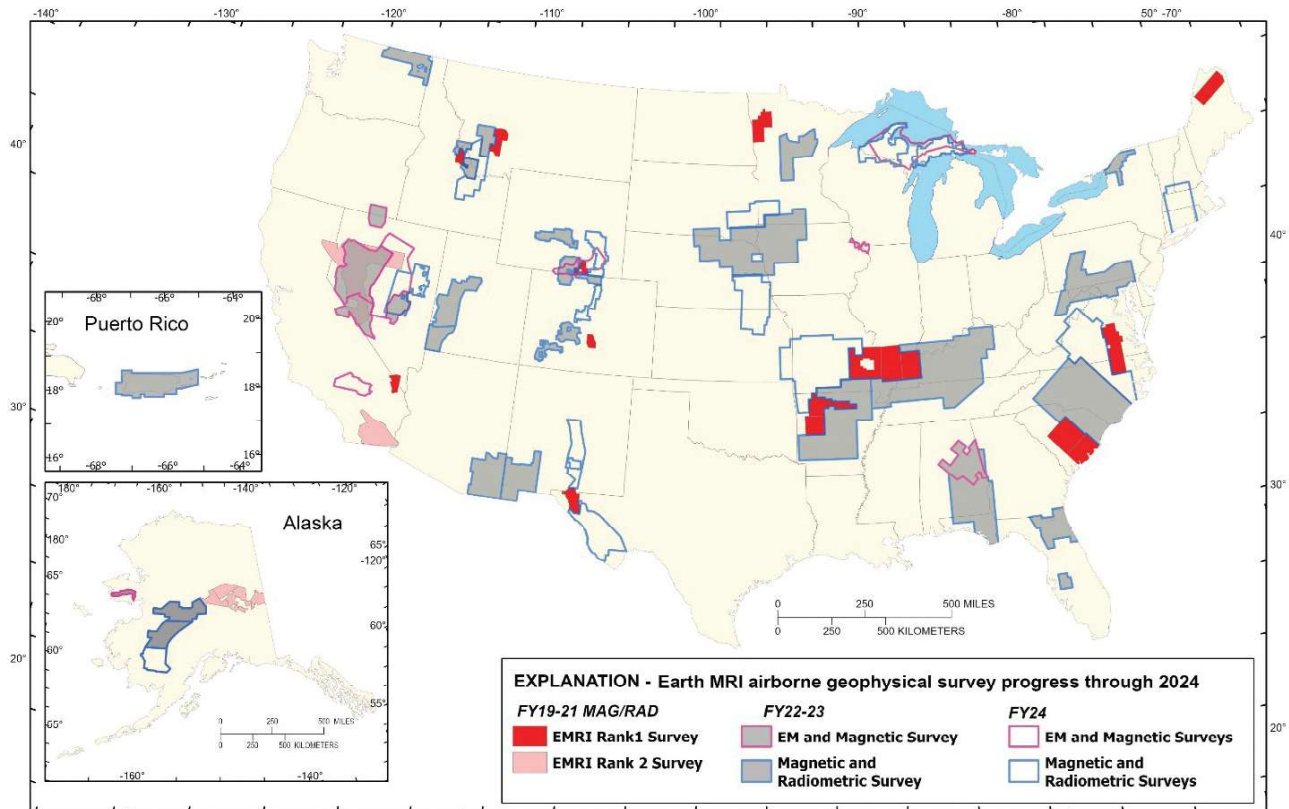
Earth MRI project design and data collection activities are planned and implemented on an annual basis, and priorities are established using critical mineral focus areas that are mapped across the nation (Fig. 4; Dicken et al., 2022; Hammarstrom et al., 2023a and references therein). The focus areas identify the presence of one or more of the 23 mineral systems that may host mineral deposits enriched in critical minerals (Hofstra and Kreiner, 2020; Dicken et al., 2022). The Earth MRI focus areas were developed in partnership with state geological surveys and they provide an initial, broad screening tool for targeting areas for new data acquisition. The mineral systems framework identifies all the deposit type(s) 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, together with published information about the size and status of each entry (Hammarstrom et al., 2023b). In the database, the deposits are given a ranked value determined from their critical mineral status (that is, past, current or future producers) and the presence or absence of known reserves or resources. Among 681 known deposits contained in the database, more than 200 entries were identified as having documented resources but with no evidence of present or past production, thus representing the potential for untapped critical mineral resources in these nations. The mineral deposit database was

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Figure 5

Outlines of Earth MRI airborne magnetic-radiometric (red polygons and blue outlines) and electromagnetics surveys (magenta outlines) from 2019 through 2024. Solid red polygons indicate surveys that are completed and publicly available through USGS ScienceBase. Shaded polygons indicate surveys that are in progress. Unshaded polygons show surveys that have been contracted but have not yet begun. More information on each survey and links to data, where available, can be found on the Earth MRI Acquisitions Viewer (<https://ngmdb.usgs.gov/emri/>).



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 deposits and mineral systems and to identify the most prospective geologic systems and regions for new data collection through Earth MRI.

The initial years of Earth MRI data collection focused on modernizing geophysical, geologic and topographic (elevation) data sets across the nation. Since its inception in 2019, Earth MRI has funded all or part of 26 new lidar surveys in 17 different states through the USGS 3D Elevation Program (3DEP), contributing new high-resolution topographic data that cover more than 924,600 km² (357,000 sq miles) of the United States. To date, 100 geologic and geochemical mapping projects have been funded across 35 different states and territories to better understand connections between the bedrock geologic framework and associated mineral resources in each area. Some of the

projects involve detailed, systematic geologic mapping, whereas others involve systematic sampling for modern geochemical data across mineral systems spanning multiple states. Earth MRI has contracted for 49 airborne magnetic and radiometric surveys following the Rank 1 specifications of Drenth and Grauch (2019) that have more than doubled the amount of high-quality magnetic data for the conterminous United States and cover the entire island of Puerto Rico (Fig. 5). Earth MRI has also funded six airborne magnetic surveys in Alaska designed to Rank 2 specifications (Drenth and Grauch, 2019) that were contracted and published by the Alaska Division of Geological and Geophysical Surveys (Fig. 5). These new data have more than quadrupled the amount of previously available high-quality magnetic data in Alaska. Collectively, airborne magnetic and radiometric surveys are essential for mapping and modeling the bedrock geologic framework of the United States, particularly 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 systems (for example, Shah et al., 2021; Wang et al., 2023).

The projects already summarized and described in more detail in this article are all shown in the Earth MRI Acquisitions Viewer (<https://ngmdb.usgs.gov/emri/>), a web portal that is updated regularly and provides information on all Earth MRI data collection activities and includes project status, brief project descriptions, points of contact and links to data for projects that are complete. Completed datasets are published as USGS data releases on ScienceBase (<https://www.sciencebase.gov/catalog/>) or by the state geological survey that conducted the work.

Earth MRI data collection conducted by state geological surveys. A significant part of Earth MRI's activity in 2024 involved partnerships with state geological surveys across the nation. State geological surveys conduct new geologic mapping and reconnaissance geochemical surveys that provide insights into critical mineral focus areas. In 2024, Earth MRI funded 22 new geologic or reconnaissance geochemical mapping projects through cooperative agreements with 25 different state geological surveys. State geologic mapping projects addressed a range of topics and regions including the alkaline igneous belt of western Texas; heavy mineral sands in the coastal plain of South Carolina, North Carolina and Virginia; the Pyrites complex in the Adirondack lowlands of western New York; the Cuyuna Range in central Minnesota; Ordovician phosphatic strata in Iowa and Illinois; and volcanogenic massive sulfide deposits in Nevada. Reconnaissance geochemical projects that started in 2024 are investigating molybdenum and tungsten deposits across Texas, New Mexico, Arizona and California; lead-zinc deposits in the tri-state district of Missouri, Kansas and Oklahoma; Permian evaporites in eastern Kansas; Paleozoic black shale and phosphate in Oklahoma; and alunite deposits in southwestern Utah.

Finally, Earth MRI has 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 is focused on 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, and preservation and potential geochemical reanalysis of legacy rock samples

and drill core. In 2024, 21 state geological surveys were supported by NGGDPP, enabling them to preserve vital geologic and geophysical data and samples that address Earth MRI needs and priorities. The results of these projects are made publicly available through multiple web sites that may include published reports by state geological surveys, the USGS National Index of Borehole Information (NIBI, <https://webapps.usgs.gov/nibi/>), and (or) the USGS Registry of Scientific Collections (ReSciColl, <https://webapps.usgs.gov/resicoll/>). New geochemical data resulting from mapping, mine waste and data preservation projects are published in a continuous USGS data release on ScienceBase that is versioned periodically as new data become available (U.S. Geological Survey, 2021).

Geophysical surveys

Airborne magnetic and radiometric surveys.

In 2024, more than \$40 million was invested to collect new, high-resolution airborne magnetic and radiometric geophysical data in multiple regions of the United States to aid in bedrock geologic mapping and modeling of regions prospective for hosting critical mineral resources. The goal is to combine the deeper-sensing geophysical data with traditional geologic mapping efforts at the surface to understand the nature of the magmatic intrusions and structures associated with the region's mineral deposits. Magnetic data can image the dip and depth of structures and the shapes of intrusions kilometers beneath the Earth's surface. These data are also sensitive to the amount of the mineral magnetite in rocks, which helps to distinguish between different igneous rock compositions, particularly where important units are buried or obscured under younger sedimentary cover. Radiometric data record naturally occurring radiation emitted from minerals at shallow depths (about 30 cm), aiding in geologic mapping efforts in difficult terrain, as well as imaging some types of mineral alteration that may signal the presence of economic deposits. Figure 5 shows the outlines of planned, active and completed airborne surveys designed and contracted by Earth MRI from 2019 through 2024, including those that are described below. New airborne geophysical surveys funded for data collection in Alaska will continue data collection across the Kuskokwim Mountains region in the southwestern part of the state. In addition to being part of the world-class Tintina gold belt, the region also contains known tin, REE, tungsten and antimony deposits and has high potential for other undiscovered critical mineral resources. In the western United States, magnetic-radiometric surveys funded

in 2024 cover an area greater than 103,000 km² (39,700 sq miles) in parts of Nevada, Montana, Idaho, Wyoming, Colorado, New Mexico and western Texas. Companion geological mapping, reconnaissance geochemical mapping and mine waste investigations were also started in many of these states. New geophysical data collection in New Mexico and western Texas focused on a regional alkaline igneous belt that extends from the Jicarilla Mountains, NM, south to the Big Bend region, TX. When combined with a previously completed airborne magnetic-radiometric survey in western Texas, the new data will cover a region exceeding 19,424 km² (7,500 sq miles). New airborne geophysical surveys in Colorado and Wyoming focus on the northeastern extent of the Colorado Mineral Belt and Laramie Mountains, respectively. When completed, these and previously funded surveys will cover and connect with active Earth MRI geophysical surveys in northern Colorado and southern Wyoming, providing new insights into multiple mineral systems in the region. New surveys in Idaho and Montana were developed across the states' borders, bridging active surveys focused on the Pioneer batholith to the east and Idaho cobalt belt to the west. New airborne magnetic-radiometric data collection in Nevada will cover approximately 22,200 km² (8,570 sq miles) of the east-central part of the state. Survey targets include Carlin, porphyry copper, reduced intrusion-related and lacustrine evaporite mineral systems that are prospective for critical minerals such as tungsten, tin, lithium, antimony, beryllium and tellurium.

In the central United States, a new airborne magnetic-radiometric survey spans more than 79,800 km² (30,800 sq miles) of Missouri and adjacent parts of northern Arkansas and eastern Kansas to investigate basin-brine path, IOA-IOCG, and marine chemocline mineral systems. These systems underlie historical mining districts such as the tri-state Mississippi Valley-Type District, the Central Missouri Barite-Lead District and the Missouri Cheltenham Fireclay District, and the survey area also encompasses regionally extensive Paleozoic phosphatic strata that are prospective for REEs (for example, Emsbo et al., 2015). Another new geophysical survey was initiated over parts of southeastern Nebraska and northeastern Kansas, focused on mapping buried crystalline rocks related to the Precambrian Midcontinent Rift System and the Paleozoic Elk Creek carbonatite. In the north-central United States, two new surveys focused on a region around Sioux Falls, SD, and the Upper Peninsula of Michigan and northern Wisconsin. The Sioux Falls survey builds on

a larger regional survey started in 2022 that investigates concealed Precambrian basement rocks that are associated with major geologic structures and represent a variety of mineral systems. The new survey in northern Michigan covers a large region of variably exposed Precambrian rocks that have known or suspected potential to host nickel, platinum-group elements and graphite in addition to many other critical mineral commodities.

In the eastern United States, two major airborne magnetic-radiometric surveys were initiated in 2024. A new survey covering parts of Connecticut, Massachusetts, Rhode Island, New Hampshire and Vermont will investigate mineral systems and geologic provinces that have potential to host cobalt, nickel, graphite, tin and lithium deposits. The survey was also designed to aid in mapping the distribution of rocks containing pyrrhotite, a sulfide mineral that is common in the region and presents infrastructure challenges when incorporated into concrete. In the southeast, a new survey extends from the coastal plain of North Carolina across the Piedmont and Appalachian Mountains of Virginia and West Virginia. The survey will cover prospective heavy mineral sand deposits enriched in titanium, zirconium and REEs that are common throughout the coastal plain and are being mapped in greater detail using active and completed Earth MRI magnetic-radiometric surveys. The survey will also cross historical mining districts and mineral systems in the Appalachian Mountains that have known or suspected potential for hosting tungsten, zinc, tin, barite, chromium, manganese and cobalt.

Seven Earth MRI airborne magnetic and radiometric surveys from prior years were published in 2024. The USGS published data releases for six different surveys covering the Republic area of northeastern Washington (Staisch et al., 2024), the porphyry belt of southwestern New Mexico (Bultman, 2024), the Salton trough of southern California (Glen and Earney, 2024), the Colorado Mineral Belt in southwestern Colorado (U.S. Geological Survey, 2024b), the Medicine Bow Mountains in southern Wyoming (U.S. Geological Survey, 2024c), and the South Pass and Granite Mountains region of central Wyoming (U.S. Geological Survey, 2024d). The South Pass and Granite Mountains survey was funded by the state of Wyoming, designed by the Wyoming State Geological Survey, and contracted by the USGS. One additional Earth MRI magnetic and radiometric survey was published by the Alaska Division of Geological and Geophysical Surveys for the Sischu Mountains part of the Kuskokwim

mineral belt in central Alaska (Emond et al., 2024a).

Airborne electromagnetic surveys. In 2024, Earth MRI invested approximately \$3 million in regional and smaller-scale airborne electromagnetic (AEM) surveys in the western and central United States. Two multiyear survey efforts began in Wyoming and Michigan, respectively (Fig. 5). The Wyoming AEM survey will begin in the southern part of the state and will focus on the Cheyenne Belt, a major Precambrian tectonic zone that juxtaposes disparate mineral systems associated with crystalline basement terranes of different ages on either side. The tectonic zone outcrops in limited exposures across multiple mountain ranges across southern Wyoming, but the structure is otherwise concealed by younger sedimentary cover across much of its extent. The AEM survey in the upper peninsula of northern Michigan and environs will aid mapping and modeling of Precambrian graphite-bearing strata in the region, in addition to mafic magmatic rocks associated with the Midcontinent Rift System that contain nickel, cobalt and platinum-group elements. The Michigan AEM survey will also be optimized in selected areas to facilitate groundwater modeling in support of Tribes in the region. A focused AEM survey was planned and conducted around Dubuque, IA, to investigate phosphate-rich strata that underlie portions of Illinois, Iowa and Wisconsin. The survey area covers a phosphate horizon in Ordovician shale that is enriched in REEs, and the survey was designed to map the location and thickness of the shale unit containing the phosphate horizon. The survey area also overlaps the Upper Mississippi Valley mineral district in southwestern Wisconsin that is known to host zinc and lead mineralization in other Ordovician strata.

Data from two Earth MRI airborne electromagnetic surveys from prior years were published in 2024. The USGS published one data release containing electromagnetic and magnetic data over the Alabama graphite-vanadium belt and surrounding regions (U.S. Geological Survey, 2024a). The Alaska Division of Geological and Geophysical Surveys published airborne electromagnetic data over the Kigluaik, Bendeleben and Darby Mountains in western Alaska (Emond et al., 2024b). Both surveys were conducted to aid mapping and assessment of graphite resource potential in the two regions.

Airborne hyperspectral remote sensing surveys. In 2024, Earth MRI invested more than \$5 million in new hyperspectral remote

sensing data in the western United States. Earth MRI began funding the collection of high-altitude regional hyperspectral data in 2022 through a partnership with NASA using the Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS-Classic). Secondary thermal infrared (TIR) sensors such as MASTER and HyTES are also being used as available. New hyperspectral data have been collected over parts of California, Nevada, Arizona and New Mexico with an average pixel size ranging from 10 to 17 m (32 to 55 ft), and the reflectance data are being calibrated by concurrent ground studies conducted by USGS scientists. In 2024, new data coverage totaled approximately 367,780 km² (142,000 sq miles) of the western and southwestern United States. When combined with data collected through Earth MRI in 2023 and with legacy data funded by the USGS Mineral Resources Program in 2018, current coverage of these hyperspectral data exceeds 802,900 km² (310,000 sq miles), which is presently the largest terrestrial area of contiguous hyperspectral coverage at 15-m (50-ft) spatial resolution. When available, imaging spectrometer data will be accessible through the NASA Geological Earth Mapping Experiment website (<https://impact.earthdata.nasa.gov/casei/campaign/GEMx>).

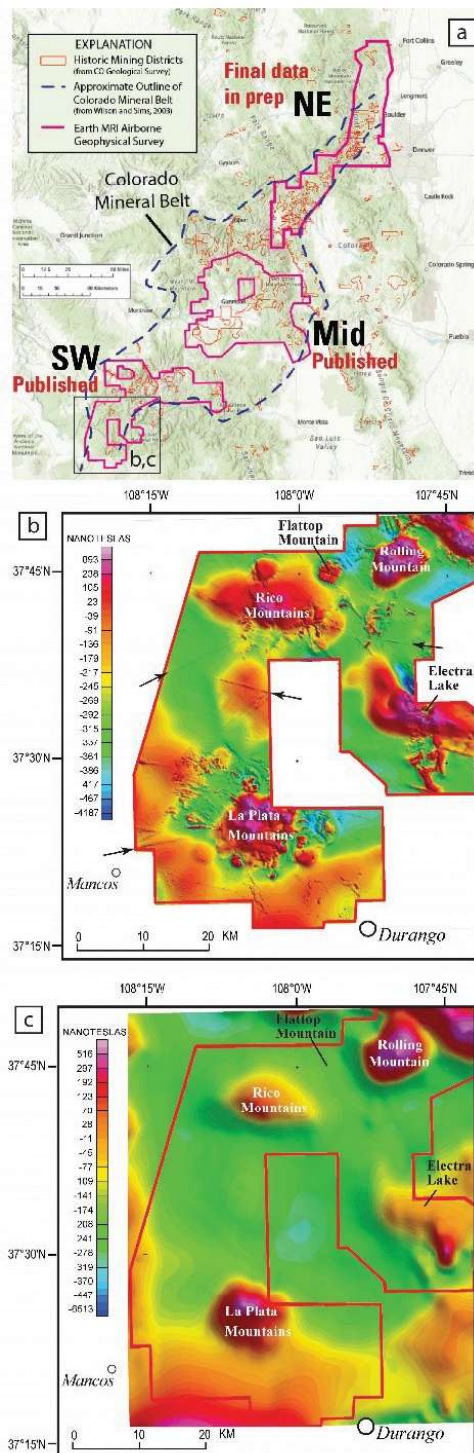
In 2024, Earth MRI also conducted a district-scale hyperspectral survey over selected areas of eastern Arizona and western New Mexico. The selected areas included active and legacy mine sites and surrounding bedrock areas with known or suspected critical mineral resources potential. Hyperspectral data were collected at lower altitudes by a commercial vendor using 2.5-m resolution FENIX (very-near infrared, near infrared and short-wavelength infrared) and 5.1-m OWL (long-wavelength infrared) sensors. The data were collected concurrently with NASA AVIRIS overflights, providing a key opportunity to investigate and calibrate spectral responses recorded by different sensors at different resolution and altitude.

Airborne magnetic and radiometric survey of the Colorado Mineral Belt. The Colorado Mineral Belt is a region extending from southwestern through central Colorado that is characterized by overlapping Mesozoic to Cenozoic magmatism, associated mineralization and a long history of mining (for example, Rosera et al., 2021). There are known critical mineral associations with mineral systems that host ore deposits throughout the region, but many aspects of the geologic and metallogenic evolution remain incompletely understood.

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Figure 6

USGS Earth MRI geophysical survey over the Colorado Mineral Belt. (a) Overview map showing the different survey blocks and state of completion as of March 2025. (b) Subset of reduced-to-pole magnetic map from the Southwest block of the Colorado Mineral Belt survey (U.S. Geological Survey, 2024b). Selected intrusion locations are labeled, black arrows denote probable dikes. (c) Previous generation of reduced-to-pole magnetic data in this region (Oshetski and Kucks, 2000), with the same intrusions labeled.



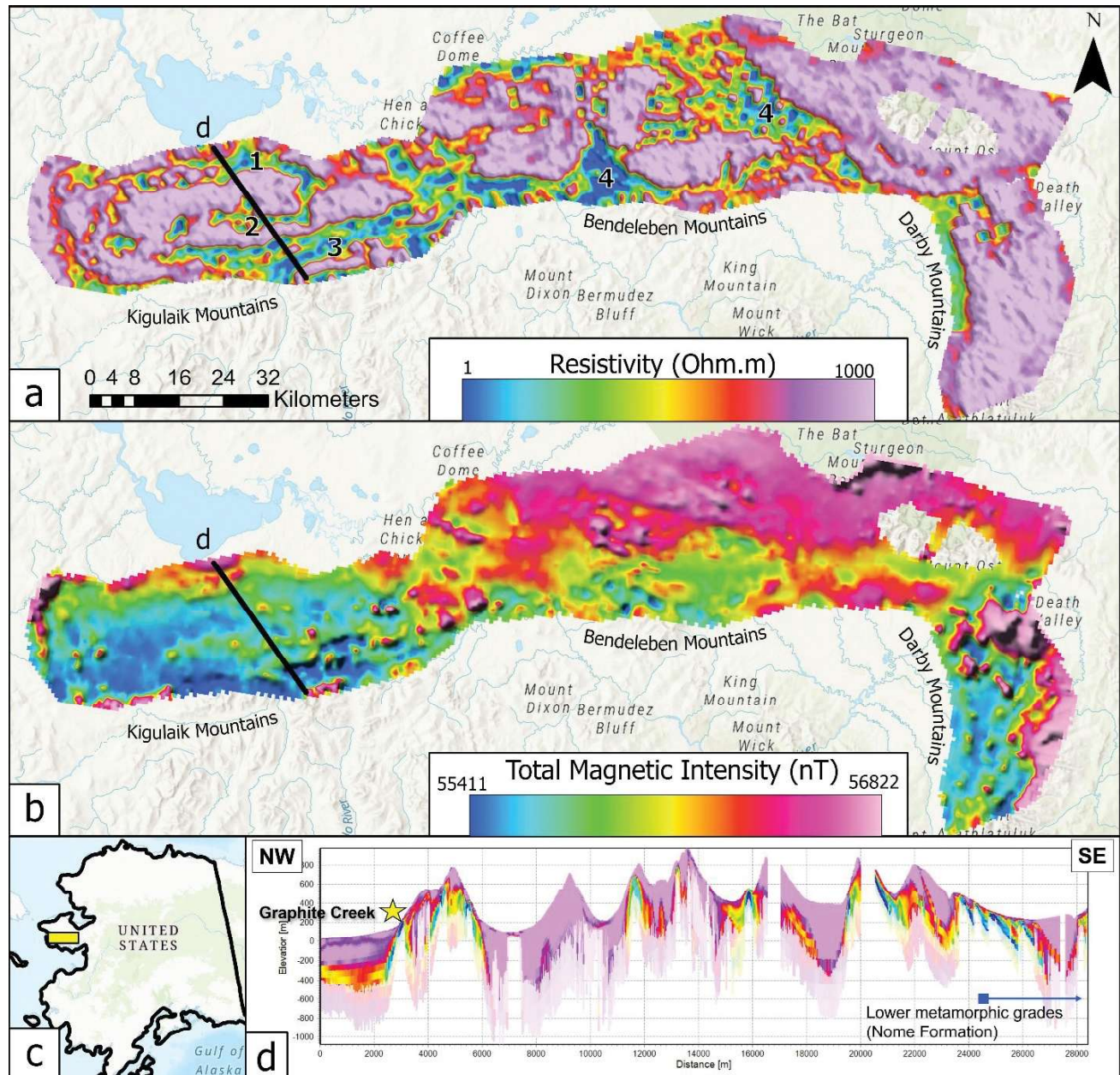
Furthermore, many parts of the mineral belt lack modern, high-quality geophysical data and detailed, systematic geologic mapping. Beginning in the fall of 2023, the USGS began collecting high-resolution magnetic and radiometric data over the Colorado Mineral Belt using a low-flying helicopter because of the rough terrain.

The Earth MRI magnetic and radiometric survey of the Colorado Mineral Belt was split into three blocks — Southwest, Mid (or Central) and Northeast (Fig. 6). The outlines are irregular to avoid areas with restricted airspace. Data acquisition is complete for all blocks. Data from the Southwest and Mid blocks have been published (U.S. Geological Survey, 2024b; U.S. Geological Survey, 2025) and the Northeast block is in the process of publication. Figure 6 shows a comparison from the previous generation of magnetic data (Fig. 6; Oshetski and Kucks, 2000) and the recently acquired Earth MRI magnetic data from the Southwest block (Fig. 6) after application of a reduction-to-pole transformation to account for latitudinal variations in Earth's magnetic field. The increased detail visible in the higher resolution magnetic data reveals the buried lateral extent of several intrusions associated with mineral deposits. For example, compared to the previous generation of magnetic data, the new data show much finer-scale features in intrusions beneath the La Plata Mountains, site of the porphyry Cu–Ag–Au–Pt metals deposit in the Allard stock (Werle et al, 1984). The level of detail visible in the intrusion beneath Rolling Mountain is vastly improved. The buried extent of the mapped laccolith beneath Flattop Mountain is now apparent where data were missing in the previous magnetic survey. Several possible dikes are also visible as narrow linear features in the new magnetic data (Grauch and MacQueen, 2024). Both broad and detailed features in the magnetic map at the intrusive complex in the Rico Mountains suggest that the complex is wider and more elongated compared to currently mapped surface exposures (Grauch and MacQueen, 2024).

Likewise, high magnetic values extend much farther to either side of mapped Proterozoic rocks at Electra Lake, suggesting that they are more extensive below the surrounding younger rocks than observed at the surface (Grauch and MacQueen, 2024). The improved delineation of these intrusions, particularly in areas of sedimentary cover or rugged terrain, permits more detailed and complete mapping of geologic units with the potential to host economic deposits of critical minerals, supporting mineral assessment efforts.

Figure 7

Preliminary results from the airborne electromagnetic and magnetic survey in the Seward Peninsula, AK (Emond et al., 2024a,b). (a) Electrical resistivity at a depth of 275 m derived from the electromagnetic data. Numbers 1-4 mark pronounced low resistivity zones discussed in the text. (b) Gridded total magnetic intensity. Note the magnetic data are not reduced to pole, and so anomalies may be slightly shifted away from their sources. (c) Context map showing the extent of (a) and (b). (d) NW-trending cross section through the resistivity models along the profile shown in (a) and (b), the yellow star marks the approximate location of the Graphite Creek Deposit, the arrow to the right indicates the general extent of lower metamorphic grades (Amato and Miller, 2004).



Airborne electromagnetic and magnetic survey of the Seward Peninsula, AK. The Kigluaik Mountains in the Seward Peninsula of Alaska host the largest-known flake graphite resource in the United States (Case et al.,

2023). The neighboring Bendeleben and Darby mountain ranges share a similar tectonic history to the Kigluaik Mountains, all experiencing high metamorphic grades (amphibolite to granulite facies) and containing rocks with high carbon

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Table 1

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

Mineral deposit type	Potential critical mineral commodities
Arsenide veins	As, Bi, Co, F, Ni, REEs, Te, W, Zn
Carlin-type gold	As, Sb
High Sulfidation epithermal	Te, Bi, As, Sb
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, F, Ga, Ge, In, Sn, Zn, Ba
Pegmatite	Be, Cs, Li, Nb, Sc, Sn, Ta
Phosphorite	Cr, F, REEs
Polymetallic sulfide skarn, replacement epithermal	Mn, Ge, Ga, In, Bi, Sb, As, W, Te
Porphyry Cu-Mo	Bi, Co, PGMs, Te
Sediment-hosted copper	Co, PGMs, Re, Ga, Ge, V, U
Superior iron	Mn, Co
Tungsten skarn and veins	Bi, Mn, Sc, W
Volcanogenic seafloor massive sulfide	Co, Bi, Te, In, Sn, Ge, Ga, Sb

content — key ingredients for graphite formation (for example, Buseck and Beyssac, 2014; Case et al., 2023). Over two field seasons in 2023 and 2024, the USGS, in collaboration with the Alaska Division of Geological and Geophysical Surveys (DGGS), contracted an AEM survey over the Kigluaik, Bendeleben and Darby Mountains to aid in assessing the potential for undiscovered flake graphite deposits. Graphite is an electrically conductive material that can be directly mapped using electromagnetic techniques that are sensitive to the resistivity (the inverse of conductivity) of the rocks. Rocks with a graphite content as low as 1 weight percent can decrease bulk resistivity by orders of magnitude (to less than 1 Ω -m) compared to similar nongraphitic lithologies. The AEM survey also collected magnetic data along flight lines; together, these data will assist in improving geologic mapping in the region, particularly in the largely unmapped Bendeleben and Darby Mountains.

Airborne EM and magnetic data have been released; Fig. 7 shows gridded preliminary resistivity models at a depth of 275 m (902 ft) and gridded total magnetic intensity data (Emond et al., 2024b). In the Bendeleben and Darby Mountains, granitic plutons display high resistivity and low magnetic intensity, while a general NW structural grain is apparent in the Bendeleben Mountains. A resistivity cross section across the Kigluaik Mountains (Fig. 7) shows NW dipping units on the NW side of the range and SE dipping units on the SE side of the range, consistent with the uplifted dome

structure of the Kigluaik Mountains (Amato and Miller, 2004). Very low resistivities are imaged throughout the survey area, including (1) in the area of the Graphite Creek prospect, (2) in the center of the Kigluaik Mountains, (3) in a wide ENE trending band on the southeast flank of the Kigluaik Mountains, as well as (4) on the southwest edge and the center of the Bendeleben Mountains. Not all graphite is created equal, however. Recent field reconnaissance found microcrystalline, rather than flake graphite in rocks on the southeast edge of the Kigluaik Mountains, as well as in a low-resistivity area on the southwest side

of the Bendeleben Mountains (MacQueen et al., 2024), consistent with reported lower metamorphic grades in these areas (Amato and Miller, 2004).

Mine waste characterization

Critical mineral resources that may reside above ground in mine waste continue to be a priority for USGS research. Noteworthy accomplishments over the past year include an assessment of critical mineral deportment at the Copperton mill at Rio Tinto's Bingham Canyon Mine, in Utah (Seal et al., 2024) and a literature review of the state of knowledge regarding the toxicity of critical minerals (White et al., 2024). 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.

Meeting future demand for byproduct critical minerals may be especially challenging because their supply, by definition, relies on the production of a primary commodity such as copper, lead, zinc, gold or silver, among others. One approach is to investigate the byproduct critical mineral potential of mine waste at abandoned, inactive and active mine sites. Many critical mineral commodities had no or limited uses two or three decades ago, which destined them to waste streams at mining operations. Earth MRI includes both mine waste inventory and the mine waste characterization components, which continue to receive interest from state geological surveys. The mine waste inventory

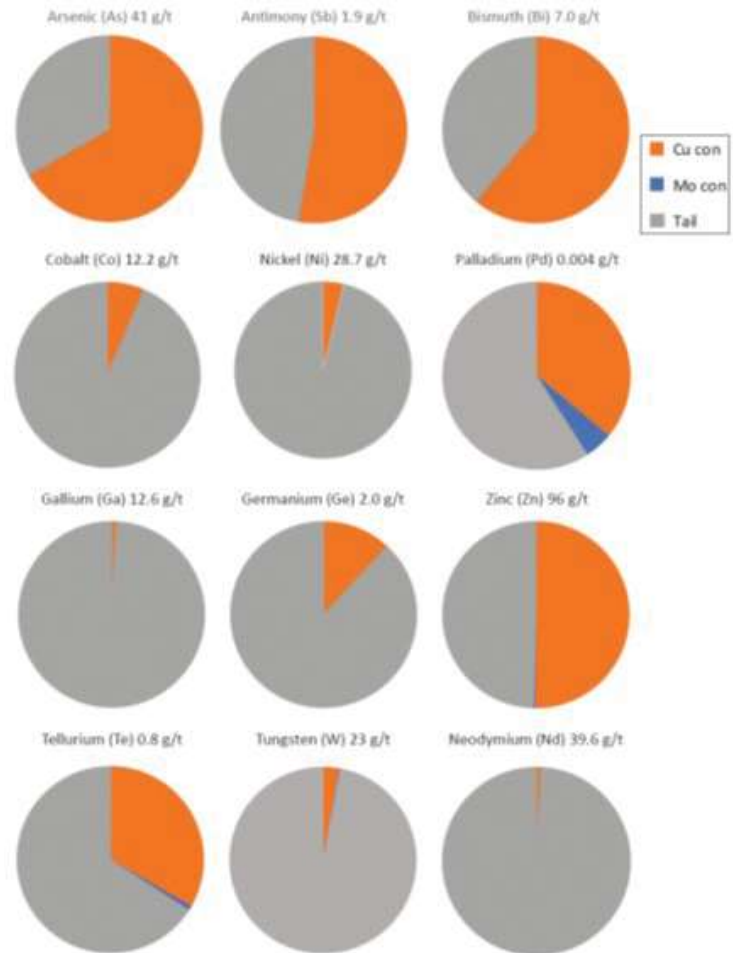
Figure 8

Department of selected critical mineral commodities among the Cu concentrate, Mo concentrate, and tailings based on mass-balance calculations (Seal et al., 2024). The concentration of each element in the mill feed is indicated at the top of each pie diagram.

activity provides funding to states to compile and create geospatial records and related metadata of mine waste features, with plans to merge into the USGS's USMIN database (<https://www.usgs.gov/centers/gggsc/science/usmin-mineral-deposit-database>). Nine states received inventory grants in the 2024 cycle. The mine waste characterization activity funds state geological surveys to sample mine waste to assess its critical mineral potential. The sampling is done following prescribed protocols and samples are submitted to the USGS for analysis to ensure that an internally consistent data set emerges from this national effort. The states have some flexibility in customizing their studies beyond the prescribed samples and protocols to address local interests and concerns. The analytical data are published as a USGS data release (U.S. Geological Survey, 2021), and the state geological surveys are required to publish final reports of findings. Eight states received mine waste characterization grants in 2024: California, Illinois, Michigan, Missouri, Nevada, New Mexico, Oklahoma and Utah, of which Illinois, Missouri and New Mexico are repeat awardees. Collectively, the studies funded in 2022 to 2024 are investigating mine waste from more than 14 mineral deposit types that could contain more than 40 critical mineral commodities (Table 1).

Another approach in identifying opportunities for the recovery of potential byproduct commodities is to investigate and understand the department of critical minerals at the earliest stages of ore processing at active mines. Ore processing circuits are optimized for the recovery of primary commodities at a mine. Most byproducts are recovered when a residue from an ore-processing activity is identified as having anomalous concentrations of a specific element and the value of the commodity exceeds the cost of recovery.

The USGS is partnering with Rio Tinto to better understand the department of critical minerals at the Copperton mill at the Bingham Canyon (Kennecott Copper) Mine. Preliminary results of the USGS study were presented at the recent International Conference on Acid Rock Drainage in Halifax, Nova Scotia, Canada in a session on "innovation" (Seal et al., 2024). The research focused on the three main outputs from the Copperton mill from a single monthly composite sampling: the copper concentrate, the molybdenum concentrate and tailings. Selected critical mineral commodities illustrate their variable behavior during the earliest stages of ore processing at the mine (Fig. 8). For example, the semimetal commodities arsenic, antimony and bismuth have similar departments, the



majority going with the copper concentrates and the rest mostly reporting to the tailings. The predominance of these elements in the copper concentrate reflects their occurrence in copper minerals such as enargite and tennantite (Brodbeck et al., 2022). Some tellurium is in the copper concentrate. Since 2022, Bingham Canyon is an important source of byproduct tellurium from copper refining (<https://www.riotinto.com/en/news/releases/2022/rio-tinto-starts-tellurium-production-at-kennecott>). The chalcophile ("sulfur-loving") nature of nickel and cobalt suggests that their department to tailings may be associated with trace nickel and cobalt sulfide minerals or with pyrite. The near exclusive department of neodymium — an REE — and tungsten to tailings suggests that they are hosted by nonsulfide heavy minerals such as monazite and scheelite, respectively. The USGS

is continuing research to better understand the mineral hosts of these commodities.

Given the plethora of critical mineral commodities, our state of understanding of these elements is insufficient to inform decision-making. Knowledge of their environmental behavior and health effects can help to support the development of safe, environmentally responsible and sustainable supplies. The USGS developed a method to identify knowledge gaps and prioritize research on topics encompassing the occurrence and cycling, geochemistry, bioavailability and toxicity of these elements (White et al., 2024). The study focused on review papers as a tractable metric from which to assess interest and depth of knowledge. The survey revealed a range of knowledge about some critical mineral commodities, going from rubidium, with just four review papers identified, to arsenic with 150 review papers. The commodities that are currently among the most critical — cobalt and gallium (Nassar and Fortier, 2021) — fall somewhere in the middle with between 20 and 40 review papers each; however, most of the available papers focus on occurrence, geology and geochemistry (White et al., 2024). This study provides a road map for potential future research into critical minerals.

Conclusion

Through various research activities across critical minerals 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 can help to inform stewardship of natural resources and decision-making. ■

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