Prepared in cooperation with the Association of American State Geologists

Focus Areas for Data Acquisition for Potential Domestic Resources of 11 Critical Minerals in the Conterminous United States, Hawaii, and Puerto Rico—Aluminum, Cobalt, Graphite, Lithium, Niobium, Platinum-Group Elements, Rare Earth Elements, Tantalum, Tin, Titanium, and Tungsten

Chapter B of
Focus Areas for Data Acquisition for Potential Domestic Sources of Critical Minerals

Open-File Report 2019–1023
Version 1.1, July 2022

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph of the discovery outcrop of the J-M platinum-palladium reef in the Stillwater Complex, Montana. The Stillwater Complex is an example of a nickel-copper-PGE sulfide deposit in a mafic magmatic mineral system. Photograph by Micheal L. Zientek, U.S. Geological Survey.

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By Jane M. Hammarstrom, Connie L. Dicken, Warren C. Day, Albert H. Hofstra, Benjamin J. Drenth, Anjana K. Shah, Anne E. McCafferty, Laurel G. Woodruff, Nora K. Foley, David A. Ponce, Thomas P. Frost, and Lisa L. Stillings

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Preface

Pursuant to Presidential Executive Order (EO) 13817 of December 20, 2017, "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals" (82 FR 60835–60837), the Secretary of the Interior directed the U.S. Geological Survey (USGS), in coordination with other Federal agencies, to draft a list of critical minerals. The USGS developed a draft list of 35 critical minerals using a quantitative screening tool (S.M. Fortier and others, 2018, USGS Open-File Report 2018–1021, https://doi.org/10.3133/ofr20181021). The draft list of 35 minerals or mineral material groups deemed critical was finalized in May 2018 (83 FR 23295–23296), although the designation of "critical" will be reviewed at least every 3 years in accordance with the Energy Act of 2020 (Public Law 116–260, 134 Stat. 2565). A "critical mineral" is defined by EO 13817, section 2, as follows:

> *Definition*. (a) A "critical mineral" is a mineral identified by the Secretary of the Interior pursuant to subsection (b) of this section to be (i) a non-fuel mineral or mineral material essential to the economic and national security of the United States, (ii) the supply chain of which is vulnerable to disruption, and (iii) that serves an essential function in the manufacturing of a product, the absence of which would have significant consequences for our economy or our national security.

Disruptions in supply chains may arise for any number of reasons, including natural disasters, labor strife, trade disputes, resource nationalism, and conflict.

EO 13817 noted that "despite the presence of significant deposits of some of these minerals across the United States, our miners and producers are currently limited by a lack of comprehensive, machine-readable data concerning topographical, geological, and geophysical surveys."

In response to the need for information on potential domestic sources of these critical minerals, the USGS launched the Earth Mapping Resources Initiative (Earth MRI). The Earth MRI is a partnership between the U.S. Geological Survey, other Federal agencies, State geological surveys, and the private sector, and it is designed to acquire the national geologic framework information essential for identifying areas with potential for hosting the Nation's critical mineral resources. The goal of the Earth MRI is to improve the geological, geophysical, and topographic mapping of the United States and to procure new data to stimulate mineral exploration to secure the Nation's supply of critical minerals.

Acknowledgments

In order to obtain information on potential domestic resources of critical minerals, studies were conducted under phase 2 of the Earth Mapping Resources Initiative (Earth MRI), a partnership between the U.S. Geological Survey (USGS) and State geological surveys. USGS scientists who participated in development of the approach adopted for this study and provided information on focus areas for the data release that accompanies this report included Allen Anderson, Pam Cossette, Poul Emsbo, Mark Gettings, Tim Hayes, John Horton, Jamey Jones, Doug Kreiner, Carma San Juan, Bradley Van Gosen, Peter Vikre, Michael Zientek, and Lukas Zurcher (all funded primarily by the USGS Mineral Resources Program).

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Many representatives from State geological surveys and the USGS participated in workshops, provided data, and identified priority areas for new data acquisition, and they are listed below.

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Cooperators for phase 2 of Earth MRI

Alaska Division of Geological and Geophysical Surveys
- Werdon, M.B.

Arizona Geological Survey
- Richardson, C.A.

Arkansas Geological Survey
- Cannon, C.
- Hanson, W.D.

California Geological Survey
- Gius, F.W.
- Key, E.

Colorado Geological Survey
- Morgan, M.L.
- O'Keeffe, M.K.

Delaware Geological Survey
- KunleDare, M.

Florida Geological Survey
- Means, G.

Geological Survey of Alabama
- VanDervoort, D.S.
- Whitmore, J.P.

Idaho Geological Survey
- Gillerman, V.S.
- Lewis, R.S.

Illinois State Geological Survey
- Denny, F.B.
- Freiburg, J.

Indiana Geological and Water Survey
- Mastalerz, M.
- McLaughlin, P.I.

Iowa Geological Survey
- Clark, R.J.
- Tassoer-Surine, S.

Kentucky Geological Survey
- Andrews, W.M.
- Lukoczki, G.

Maine Geological Survey
- Beck, F.M.
- Whittaker, A.H.

Maine Mineral and Gem Museum
- Felch, M.

Maryland Geological Survey
- Adams, R.H.
- Brezinski, D.K.
- Junkin, W.
- Ortt, R.

Michigan Geological Survey
- Harrison, W.

Minnesota Department of Natural Resources
- Dahl, D.A.

Minnesota Natural Resources Research Institute
- Hudak, G.J.

Missouri Geological Survey
- Lori, L.
- Seeger, C.M.
- Steele, A.

Montana Bureau of Mines and Geology
- Korzeb, S.L.
- Scarberry, K.C.

Nevada Bureau of Mines and Geology
- Muntean, J.L.

New Mexico Bureau of Geology and Mineral Resources
- Kelley, S.A.
- McLemore, V.T.

North Carolina Geological Survey
- Chapman, J.S.
- Farrell, K.M.
- Taylor, K.B.
- Veach, D.

Pennsylvania Geological Survey
- Hand, K.
- Shank, S.G.

South Carolina Geological Survey
- Howard, C.S.
- Morrow, R.H.

Texas Bureau of Economic Geology
- Elliott, B.A.

Utah Geological Survey
- Boden, T.
- Mills, S.E.
- Rupke, A.

Virginia Division of Geology and Mineral Resources
- Coiner, L.V.
- Lassetter, W.L.

Washington Geological Survey
- Eungard, D.W.

West Virginia Geological and Economic Survey
- Brown, S.R.
- Moore, J.P.

Western Michigan University
- Thakurta, J.

Wisconsin Geological and Natural History Survey
- Gottschalk, B.
- Stewart, E.K.

Wyoming State Geological Survey
- Gregory, R.W.
- Lynds, R.M.
- Mosser, K.

U.S. Geological Survey
- Anderson, A.K.
- Ayuso, R.A.
- Bern, C.R.
- Bookstrom, A.A.
- Bradley, D.C.[1]
- Bultman, M.W.
- Carter, M.W.
- Cossette, P.M.
- Day, W.C.
- Dicken, C.L.
- Drenth, B.J.
- Emsbo, P.
- Foley, N.K.
- Frost, T.P.
- Gettings, M.E.
- Grauch, V.J.
- Hall, S.M.
- Hammarstrom, J.M.
- Hayes, T.S.
- Hofstra, A.H.
- Horton, J.D.
- Horton, J.W.
- Hubbard, B.E.
- John, D.A.
- Johnson, M.R.
- Jones, J.V., III
- Karl, N.
- Kreiner, D.C.
- Lund, K.
- Mauk, J.L.
- McCafferty, A.E.
- Merschat, A.J.
- Nicholson, S.W.
- Ponce, D.A.
- Robinson, G.R.[1]
- San Juan, C.A.
- Shah, A.K.
- Schulz, K.J.[1]
- Siler, D.L.
- Slack, J.F.[1]
- Soller, D.R.
- Stillings, L.L.
- Swezey, C.S.
- Taylor, R.D.
- Van Gosen, B.S.
- Vikre, P.G.
- Walsh, G.J.
- Woodruff, L.G.
- Zientek, M.L.
- Zurcher, L.

[1]Emeritus.

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Conversion Factors.

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)

Multiply	By	To obtain
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	metric ton (t)
ton, long (2,240 lb)	1.016	metric ton (t)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square hectometer (hm^2)	2.471	acre
square kilometer (km^2)	247.1	acre
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)
square hectometer (hm^2)	0.003861	section (640 acres or 1 square mile)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]
millimeter per year per meter ([mm/yr]/m)	0.012	inch per year per foot ([in/yr]/ft)

Abbreviations

AASG	Association of American State Geologists
ARDF	Alaska Resource Data File
Earth MRI	Earth Mapping Resources Initiative
Ga	giga-annum
GIS	geographic information system
IOA	iron oxide-apatite
IOCG	iron oxide-copper-gold
LCT	lithium-cesium-tantalum
lidar	light detection and ranging
Ma	mega-annum
MAS/MILS	Mineral Availability System/Mineral Industry Location System
MRDS	Mineral Resources Data System
Mt	million metric tons
MVT	Mississippi Valley-type
NYF	niobium-yttrium-fluorine
REE	rare earth element
PGE	platinum-group element
PGM	platinum-group metal
ppm	parts per million
sedex	sedimentary exhalative
USGS	U.S. Geological Survey
USMIN	USGS Mineral Deposit Database
%	percent

Chemical Symbols

Ag	silver
Al	aluminum
Au	gold
Be	beryllium
C	carbon
Ca	calcium
Co	cobalt
Cs	cesium
Cu	copper
Fe	iron
Ga	gallium
Ge	germanium
H	hydrogen
Hf	hafnium
In	indium
K	potassium
Li	lithium
Mn	manganese
Mo	molybdenum
Na	sodium
Nb	niobium
Ni	nickel
O	oxygen
Pb	lead
Re	rhenium
S	sulfur
Sb	antimony
Si	silicon
Sn	tin
Ta	tantalum
Te	tellurium
Ti	titanium
U	uranium
V	vanadium
W	tungsten
Y	yttrium
Zn	zinc
Zr	zirconium

Focus Areas for Data Acquisition for Potential Domestic Resources of 11 Critical Minerals in the Conterminous United States, Hawaii, and Puerto Rico—Aluminum, Cobalt, Graphite, Lithium, Niobium, Platinum-Group Elements, Rare Earth Elements, Tantalum, Tin, Titanium, and Tungsten

By Jane M. Hammarstrom, Connie L. Dicken, Warren C. Day, Albert H. Hofstra, Benjamin J. Drenth, Anjana K. Shah, Anne E. McCafferty, Laurel G. Woodruff, Nora K. Foley, David A. Ponce, Thomas P. Frost, and Lisa L. Stillings

Abstract

In response to a need for information on potential domestic sources of critical minerals, the Earth Mapping Resources Initiative (Earth MRI) was established to identify and prioritize areas for acquisition of new geologic mapping, geophysical data, and elevation data to improve our knowledge of the geologic framework of the United States. Phase 1 of Earth MRI concentrated on those geologic terranes favorable for hosting the rare earth elements (REEs). Phase 2 continued to address the REEs and also identified focus areas for potential domestic sources of 10 more of the 35 critical minerals on the U.S. critical minerals list (aluminum, cobalt, graphite, lithium, niobium, platinum-group elements, tantalum, tin, titanium, tungsten). This report describes the methodology, data sources, and summary results for mineral systems that host these 11 critical minerals in the conterminous United States, Hawaii, and Puerto Rico; Alaska is covered in a separate report. The mineral systems framework adopted for this study links critical mineral commodities to families of genetically related mineral deposit types. The mineral systems approach is an efficient approach, providing a simultaneous evaluation of geologic terranes through aggregation of genetically related mineral deposit types that are much larger than individual ore deposits. Geologic, geochemical, topographic, and geophysical mapping provided by Earth MRI will document geologic features that reflect the extent of individual mineral systems and provide information about critical mineral deposits that may not have been recognized previously.

Each critical mineral commodity is discussed in terms of importance to the Nation's economy, modes of occurrence, mineral systems, and deposit types along with maps and tables listing examples of focus areas for each critical mineral. Important mineral systems for these critical minerals include chemical weathering systems for aluminum (bauxite); placer systems for titanium and REEs; metamorphic systems for graphite; mafic magmatic systems for platinum-group elements and cobalt; lacustrine evaporite and porphyry tin systems for lithium; and copper-molybdenum-gold (Cu-Mo-Au) systems for tungsten. REEs occur in many different mineral systems. Focus areas were developed by scientists from the U.S. Geological Survey in collaboration with scientists from State geological surveys and other institutions. This first national-scale compilation of focus areas represents an initial step in addressing the Nation's critical mineral needs by screening areas for acquisition of new data to provide the geologic framework necessary for identifying domestic sources of critical minerals.

Introduction

The U.S. Geological Survey (USGS) launched the Earth Mapping Resources Initiative (Earth MRI) in 2019 in response to a need for information on potential domestic sources of critical minerals (Day, 2019). Earth MRI is a national-scale, collaborative effort with the Association of American State Geologists (AASG) to identify and prioritize areas for acquisition of new geologic mapping, geophysical data (aeromagnetic surveys and airborne radiometric surveys), and elevation (light detection and ranging [lidar]) data to improve our knowledge of the geologic framework of the United States. This science-based program provides basic geoscience information essential for evaluating undiscovered critical mineral resource potential. In addition, new data will have applications for water and energy resources, natural hazards, and other geoscience topics.

The USGS worked with representatives from State geological surveys and other institutions to develop a series of focus areas that have potential for containing critical mineral resources and to guide the selection of priority areas for new data acquisition.

This report describes the background and methods used to define broad areas within the conterminous United States as focus areas for future geoscience research on potential sources of 11 critical minerals in nonfuel mineral deposits. A companion report addresses these topics for Alaska (Kreiner and Jones, 2020). During 2019, Earth MRI addressed the rare earth elements (REEs) as part of a phase 1 effort (Hammarstrom and Dicken, 2019). This report addresses the critical minerals chosen for phase 2, which included aluminum, cobalt, graphite (natural), lithium, niobium, platinum-group elements (PGEs), rare earth elements (REEs), tantalum, tin, titanium, and tungsten. These commodities were selected for the second phase of Earth MRI because the United States is highly reliant on imports for each and their use has increased beyond foreseeable domestic production (Fortier and others, 2018). Identification of domestic sources of these commodities could reduce the Nation's net import reliance (table 1). Future improvements in recovery and marketing of supplies could satisfy domestic consumption of some commodities. Imported critical mineral commodities are mostly produced as primary products; however, some imported and domestic critical mineral commodities are byproducts or coproducts in deposit types that produce other commodities. Such byproducts could potentially be recovered from existing domestic deposits, mine wastes, and unmined resources if technology and economic incentives for recovery exist.

The purpose of this report is to identify those areas across the Nation where acquisition of new geologic mapping data, geophysical data, and (or) detailed topographic information (provided by lidar) will enhance the ability of researchers at the USGS, State geological surveys, other Federal agencies (including land-use managers and policy makers), and resource producers to evaluate and identify areas with critical mineral resource potential. The areas under consideration for new data acquisition efforts (referred to as focus areas) defined in this report were identified on the basis of existing data. Focus areas include known deposits as well as areas that may have potential according to our understanding of the geologic characteristics of mineral deposits and mineral systems that host critical minerals. For information and methods used to define focus areas in Alaska, consult Kreiner and Jones (2020).

Table 1. Salient data for phase 2 critical minerals in 2019.

[Data from U.S. Geological Survey (2020); Withheld, data withheld to avoid disclosing company proprietary data; *, apparent consumption; Mt, million metric tons; t, metric ton; kg, kilogram; TiO_2, titanium dioxide]

Critical mineral	U.S. mine production in 2019	U.S. reported consumption in 2019	Top producer globally in 2019	Notable applications
Aluminum (bauxite)	Withheld	5.1 Mt	Australia	Aircraft, power lines, lightweight alloys
Cobalt	500 t (mine) 2,700 t (secondary from historical tailings)	9,300 t (includes secondary)	Congo (Kinshasa)	Jet engines, stainless steel, batteries
Graphite (natural)	None	52,000 t	China	Rechargeable batteries, body armor, brake linings
Lithium	Withheld	2,000 t	Australia	Rechargeable batteries, aluminum-lithium alloys for aerospace
Niobium	None (none since 1959)	9,900 t	Brazil	High-strength steel for defense and infrastructure
Platinum-group elements	12,000 kg palladium 3,600 kg platinum	80,000 kg 33,000 kg	South Africa	Catalytic converters, catalysts, dental and medical devices, computers
Rare earth elements	26,000 t (as bastnaesite concentrate)	13,000 t	China	Catalysts, aerospace guidance, lasers, fiber optics
Tantalum	None (none since 1959)	870 t*	Congo (Kinshasa)	Cell phones, jet engines
Tin	None (none since 1993)	44,000 t	China	Solder, flat-panel displays
Titanium (TiO_2 in mineral concentrates)	100,000 t	1.4 Mt*	China	Jets engines, alloys, armor
Tungsten	None	Withheld	China	Cutting and drilling tools, catalysts, jet engines

Users of this report should consider the following important caveats: (1) focus areas provide a screening tool to initiate identification of priority areas for new data acquisition, (2) many focus areas are very large and are only intended to draw attention to regions of the country that may contain critical minerals, (3) areas selected for new work will likely be small relative to the size of the focus areas, (4) discovery and development of new deposits can take a decade or longer, and (5) the number of new projects that can be initiated each year is dependent on a variety factors such as funding, land access, and availability of personnel to do the work. Furthermore, application of the geoscience framework data obtained from Earth MRI to exploration and development of critical mineral resources depends on business decisions of private industry, land-use policies, regulations, world markets, and appropriate technology for mining and processing critical minerals. Geologic availability of domestic critical mineral resources does not imply that those resources would ever be developed to solve domestic short- or long-term critical mineral needs. The priorities for various critical mineral commodities and data acquisition for the various focus areas will vary through time as Earth MRI addresses necessary local and national priorities.

This report includes a description of the methods and data sources used to delineate focus areas, followed by a section on each critical mineral. Each section includes information on the critical mineral's importance to the Nation's economy, modes of occurrence, and a discussion of applicable mineral systems. These are summarized in a table listing the deposit types and examples of focus areas that were defined for that critical mineral along with a companion map showing the focus areas. To provide perspective on the importance of each critical mineral to the Nation's economy, information on domestic production and use and world resources is included, taken directly from the U.S. Geological Survey "Mineral Commodity Summaries 2020" (U.S. Geological Survey, 2020). The full report and statistics on each critical mineral as well as other publications are available from the USGS National Minerals Information Center (https://www.usgs.gov/centers/nmic).

A related USGS data release (Dicken and Hammarstrom, 2020) depicts the focus areas in a geographic information system (GIS). Using the GIS, focus areas can be plotted on maps by region, mineral system, deposit type, or critical mineral commodity. The data release also includes tables that document the rationale for delineating the focus area along with other attributes and references.

Background

A list of 35 minerals deemed critical to the United States was finalized in May 2018 using the definition of a critical mineral as "(i) a non-fuel mineral or mineral material essential to the economic and national security of the United States, (ii) the supply chain of which is vulnerable to disruption, and (iii) that serves an essential function in the manufacturing of a product, the absence of which would have significant consequences for our economy or our national security." (Fortier and others, 2018; U.S. Department of the Interior, Office of the Secretary, 2018). Earth MRI is using a phased approach to identify areas within the United States that could host critical mineral resources. Phase 1 identified areas within the United States that are likely to host REEs. Preliminary focus areas for REEs were published as a data release by Dicken and others (2019), along with a report describing methodology (Hammarstrom and Dicken, 2019). A separate USGS report described types of REE deposits known to occur in the United States (Van Gosen and others, 2019). The USGS, working with the AASG, prioritized focus areas and selected areas for new geologic mapping, geophysical surveys, and lidar acquisition.

Data collection for priority areas with the potential for REE deposits was initiated in 2019 (fig. 1). Geologic mapping projects started in the Idaho Cobalt Belt, the Gallinas Mountains, N. Mex., and Dickenson County, Mich., along with mapping of regolith for REE potential in Maryland, and Alabama and mapping areas of potential placer deposits in Virginia and North Carolina (fig. 1). Initial studies also included high-resolution regional airborne geophysical surveys covering the Atlantic Coastal Plain from the coast near Charleston, S.C., northwestward across the Fall Zone (the boundary between igneous and metamorphic rocks of the Piedmont Province and sediments of the Atlantic Coastal Plain) to target heavy-mineral-sand deposits (paleoplacers) that contain titanium-, zirconium-, and REE-bearing minerals (Shah and others, 2019). This effort was conducted in collaboration with the USGS Earthquake Hazards Program to assist imaging of potentially seismogenic faults near Charleston, S.C., which experienced heavy damage owing to a magnitude 7 earthquake in 1886. Another survey was flown in the central United States over the Hicks Dome thorium- and REE-bearing peralkaline igneous complex, covering portions of Illinois, Indiana, and Kentucky (McCafferty and Brown, 2020). A high-resolution aeromagnetic and airborne radiometric survey in areas underlain by REE-rich phosphate horizons in northern Arkansas (fig. 1) was flown to map the aerial distribution of this important national source for heavy REEs (HREEs) and is a pilot study for geophysical mapping of other REE-enriched phosphate units in the United States. A regional survey in the southeastern Mojave Desert of California and Nevada was flown over the geologic terrane that hosts the Mountain Pass REE deposit (Ponce and Drenth, 2020), the only current producer of REEs in the United States. Superseding existing low-resolution airborne data with the high-resolution aeromagnetic and airborne radiometric data from this survey will enhance evaluation of the likelihood of other undiscovered deposits in the region.

In the fall of 2019, the USGS hosted workshops with geologists from 31 State geological surveys and 3 other institutions to refine the preliminary focus areas that were identified by the USGS for critical mineral commodities to be studied during phase 2. At the workshops, the USGS presented the mineral systems framework that has been developed to identify areas of the United States that may host critical mineral resources. The participants worked with the USGS in small groups representing subregions of the country to refine the focus areas and accompanying mineral resource data and identified needs for new geologic mapping, geophysics, and lidar acquisition. At the end of the workshops, representatives of each State presented their top priorities for new projects to start in fiscal years[1] 2020

[1]The fiscal year for the Federal Government runs from October 1 to September 30.

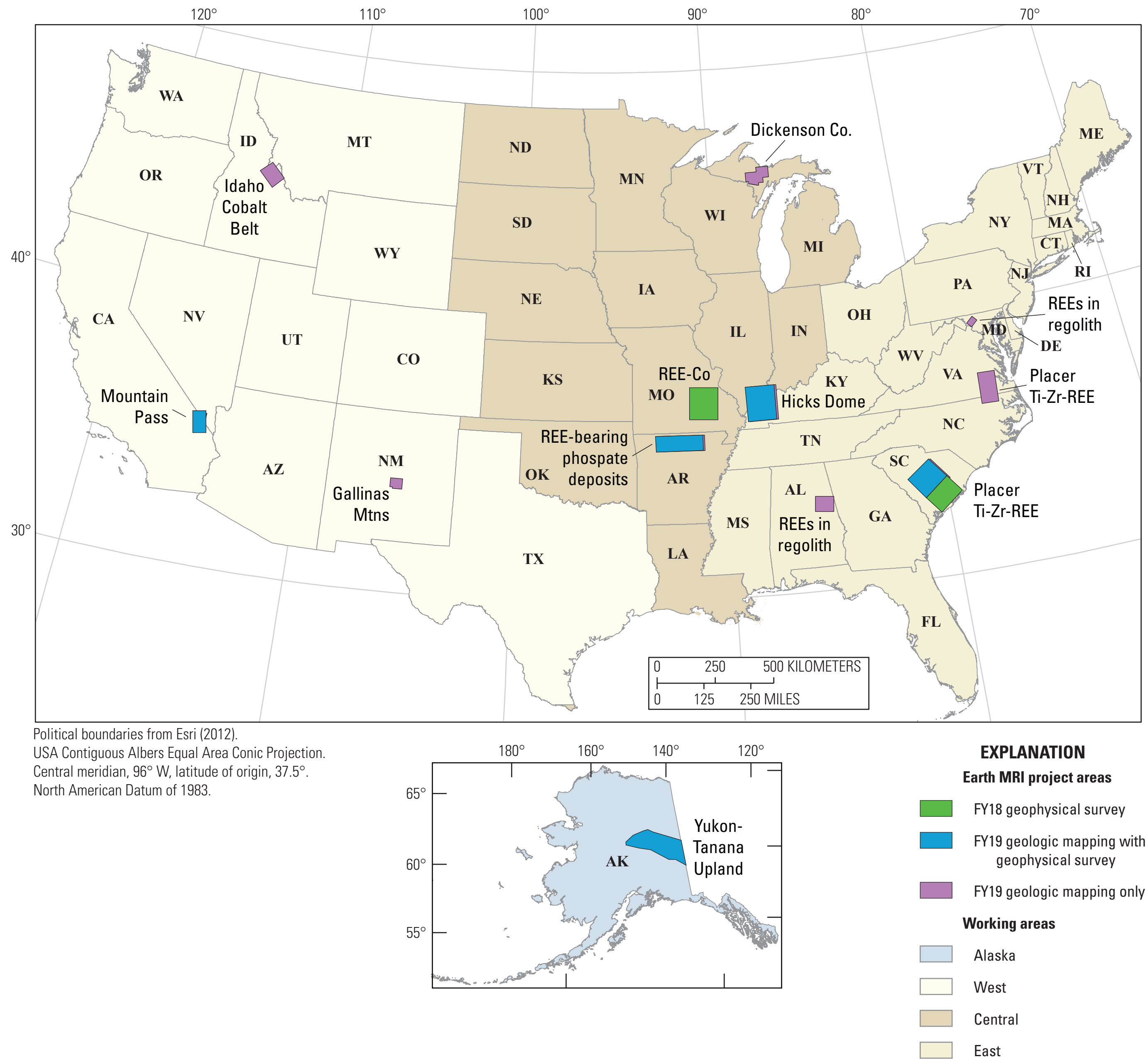


Figure 1. Map showing areas selected in fiscal years 2018 (FY18) and 2019 (FY19) for new data acquisition in phase 1 of the Earth Mapping Resources Initiative (Earth MRI). Data acquisition began in 2019. REE, rare earth element; Co, cobalt; Ti, titanium; Zr, zirconium.

and 2021 for further consideration by the USGS and AASG. In January 2020, proposed projects were evaluated and prioritized on the basis of the following criteria:

- Area contains or has potential for critical minerals,
- New framework geologic, geophysical, and (or) lidar data will materially add to delineating terranes for critical minerals,
- Land status allows for mineral exploration and development,
- New data will support other geoscience needs, and
- Synergy with ongoing USGS and State activities.

Methods

The USGS is adopting a mineral systems approach to critical minerals inventory and assessment as an efficient method to define and prioritize focus areas for 35 critical minerals (Hofstra and Kreiner, 2020). The mineral systems concept is rooted in current understanding of how ore deposits form by considering the broad geologic and tectonic framework and all the processes necessary to form ore deposits. Each mineral system has a mappable footprint where geologic processes came together in space and time to form a variety of genetically related ore deposits. Identification of one part of a large mineral system raises the possibility that related undiscovered ore deposit types may be present nearby or under cover because mineral systems have a much larger footprint than an individual deposit. Defining a mineral system requires consideration of the following processes and components (Hofstra and Kreiner, 2020):

- optimum geotectonic setting,
- energy to drive the system (for example, heat, gravity),
- source rocks for ligands and metals,
- transport media (such as metals, fluids, seawater, ligands),
- transport pathways (such as permeable structures or lithologies, lateral fluid flow, magmatic corridors),
- traps (chemical or physical), and
- distal expressions (for example, mineral, chemical, and thermal anomalies).

Critical mineral commodities occur in a variety of mineral systems with different deposit types and ages in diverse parts of the country. Aluminum, for example, can occur as bauxite in deeply weathered rocks formed in a chemical weathering system or in the mineral alunite that forms in lithocaps of porphyry copper-molybdenum-gold (Cu-Mo-Au) systems (table 2). In addition to bauxite, a chemical weathering system can include nickel-cobalt laterites, regolith (ion adsorption) REE deposits, and lithium-bearing clays, depending on what rock types were exposed to deep weathering processes. The mineral system framework developed by Hofstra and Kreiner (2020) for Earth MRI links critical minerals to genetically related deposit types that can form within a given mineral system. See appendix 1 for the complete table that describes each system and lists the deposit types and commodities associated with each system. By delineating the possible extent of a given mineral system, target areas can be selected for follow-up detailed geologic mapping by State geological surveys and acquisition of new airborne geophysical surveys under Earth MRI.

Table 2 lists the mineral systems identified for the phase 2 critical mineral commodities. Note that a mineral system can include many different types of mineral deposits (appendix 1). In some cases, the critical mineral of interest may represent a primary commodity produced from a deposit type, such as tungsten from tungsten skarns that form in porphyry Cu-Mo-Au systems. In other cases, the critical mineral can represent a byproduct or coproduct of a deposit, which is dependent primarily on the relative abundance and economics of recovery. For example, tungsten can also be produced as a byproduct from Climax-type porphyry molybdenum deposits. Additional critical minerals that were not considered for phase 2 also occur in these systems (see appendix 1).

Table 2. Mineral systems that may contain phase 2 critical minerals as primary commodities or coproducts and byproducts.

[Data from Hofstra and Kreiner, 2020. See appendix 1 for a link to the complete list of the deposit types, principal commodities, and other critical minerals associated with each mineral system as well as notation of critical minerals that have actually been produced from some deposit types in the system and those that are enriched in some deposit types in the system, but have not yet been produced. Abbreviations: PGEs, platinum-group elements; REEs, rare earth elements; IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; Cu, copper; Mo, molybdenum; Au, gold; Sn, tin]

Mineral system	Phase 2 critical mineral commodities
Alkalic porphyry	Aluminum, tungsten, PGEs
Arsenide	Cobalt
Basin brine path	Cobalt, lithium, PGEs, REEs, tin
Chemical weathering	Aluminum, cobalt, niobium, PGEs, REEs
Climax-type	Aluminum, niobium, tantalum, tin
Coeur d’Alene-type	Cobalt
IOA-IOCG	Cobalt, REEs
Lacustrine evaporite	Lithium, tungsten
Mafic magmatic	Cobalt, PGEs, titanium
Magmatic REE	Niobium, REEs, tantalum
Marine chemocline	Cobalt, REEs
Metamorphic	Graphite, REEs
Meteoric recharge	Cobalt, PGEs, REEs
Orogenic	Graphite (lump), tungsten,
Placer	Niobium, PGEs, REEs, tantalum, tin, titanium, tungsten
Porphyry Cu-Mo-Au	Aluminum, cobalt, PGEs, tungsten, tin
Porphyry Sn	Aluminum, lithium, niobium, tantalum, tin, tungsten
Reduced intrusion-related	Graphite (lump), tungsten
Volcanogenic seafloor	Cobalt, tin

Data Sources

A wide variety of data sources was used to develop focus areas and identify data gaps. Key datasets are described, along with references, in table 3. In addition to these data, State geological survey representatives provided geologic maps, mineral occurrence data, and expertise on the occurrence of critical minerals in their States. Those references are included in the tables that accompany the GIS in the related data release (Dicken and Hammarstrom, 2020).

The USGS and the U.S. Bureau of Mines, which was abolished in 1996, have a long history of studies of strategic and critical minerals. Assessments of mineral resources were conducted by these agencies at a variety of scales throughout the United States to meet mandated requirements for wilderness area studies and meet the needs of Federal land-use planners. Publications of the U.S. Bureau of Mines are available through the National Technical Report Library (https://ntrl.ntis.gov/NTRL/dashboard/searchResults.xhtml).

During World War II, the Federal Government supported exploration for many strategic and critical minerals under Federal Government Mineral Exploration-Assistance Programs; these programs fostered exploration and led to small-scale mining operations in many western States (Frank, 2016).

Table 3. Data sources used to develop focus areas for data acquisition for potential domestic sources of critical minerals.

[Abbreviations: Earth MRI, Earth Mapping Resources Initiative; USGS, U.S. Geological Survey; REEs, rare earth elements; GIS, geographic information system; USMIN, USGS Mineral Deposit Database; PGEs, platinum-group elements; lidar, light detection and ranging]

Topic	Description	Reference
Earth MRI phase 1 (REEs)	USGS Fact Sheet 2019–3007: The Earth Mapping Resources Initiative (Earth MRI)—Mapping the Nation's critical mineral resources	Day (2019)
	USGS Open-File Report 2019–1023–A: Focus areas for data acquisition for potential domestic sources of critical minerals—Rare earth elements	Hammarstrom and Dicken (2019)
	USGS data release: GIS and data tables for focus areas for potential domestic nonfuel sources of rare earth elements	Dicken and others (2019)
	USGS Circular 1454: Rare earth element mineral deposits in the United States	Van Gosen and others (2019)
USMIN data releases	U.S. Geological Survey's USMIN project is developing an updated geospatial database of mines, mineral deposits, and mineral regions in the United States, with support from the Bureau of Land Management. The current project focus is critical minerals in the United States. In addition, the USGS is digitizing mine- and prospect-related symbols on a State-by-State basis, from the 7.5-minute and the 15-minute archive of the USGS Historical Topographic Maps Collection	Products can be accessed from the USMIN web page: https://www.usgs.gov/energy-and-minerals/mineral-resources-program/science/usgs-mineral-deposit-database?qt-science_center_objects=4#qt-science_center_objects
Cobalt USMIN data release	This data release provides descriptions of more than 60 mineral regions, mines, and mineral deposits within the United States and its territories that are reported to contain enrichments of cobalt (Co). To focus the scope of this data release, the USGS reported only mined deposits and exploration prospects with past production, or resource and reserve estimates of 1,000 metric tons or more of cobalt.	Burger and others (2018)
Lithium USMIN data release	This data release provides the descriptions of approximately 20 U.S. sites that include mineral regions, mines, and mineral occurrences (deposits and prospects) that contain enrichments of lithium (Li). This release includes sites that have a contained resource and (or) past production of lithium metal greater than 15,000 metric tons. Sites in this database occur in Arkansas, California, Nevada, North Carolina, and Utah. There are several deposits that were not included in the database because they did not meet the cutoff requirement, and those occur in Arizona, Colorado, the New England area, New Mexico, South Dakota, and Wyoming. U.S. production of lithium is currently restricted to the Clayton Valley, Nevada, brine operation, but there has been previous production from pegmatite deposits. There are significant resources in lithium-bearing clay minerals, oilfield brines, and geothermal brines.	Karl and others (2019)
REEs USMIN data release	Version 4.0 of this data release provides descriptions of more than 200 mineral districts, mines, and mineral occurrences (deposits, prospects, and showings) within the United States that are reported to contain substantial enrichments of the REEs. These mineral occurrences include mined deposits, exploration prospects, and other occurrences with notable concentrations of the REEs.	Bellora and others (2019)
Tin USMIN data release	This data release provides descriptions of more than 120 mineral regions, mines, and mineral deposits within the United States that are reported to contain enrichments of tin (Sn). This data release only includes sites with publicly available records of past production of tin, or a defined resource of tin, or both.	Karl and others (2018)

Table 3. Data sources used to develop focus areas for data acquisition for potential domestic sources of critical minerals.—Continued

[Abbreviations: Earth MRI, Earth Mapping Resources Initiative; USGS, U.S. Geological Survey; REEs, rare earth elements; GIS, geographic information system; USMIN, USGS Mineral Deposit Database; PGEs, platinum-group elements; lidar, light detection and ranging]

Topic	Description	Reference
Tungsten USMIN data release	This data release reports the largest 10 percent of U.S. deposits, or mines and deposits with greater than or equal to 215 metric tons of tungsten metal (30,000 short ton units of tungsten trioxide). These deposits occur in Alaska, California, Colorado, Idaho, Montana, Nevada, New Mexico, North Carolina, Texas, Utah, and Washington. There are many smaller tungsten deposits and prospects throughout the United States in Connecticut, Maine, Missouri, New Hampshire, Oregon, Rhode Island, South Dakota, and Wyoming (Lemmon and Tweto, 1962). However, owing to the resource cutoff established for this database, smaller deposits and prospects in those States are not included.	Carroll and others (2018)
Other data releases	For several commodities that have not yet been released as individual USMIN publications, the USGS used this dataset as a source for significant locations in the United States. The point and polygon layers within this geodatabase present the global distribution of selected mineral resource features (deposits, mines, districts, mineral regions) for 23 minerals or mineral commodities considered critical to the economy and security of the United States as of 2017. This dataset includes locations for U.S. deposits of titanium, graphite, niobium-tantalum, and PGEs.	Labay and others (2017)
U.S. critical minerals reports	Professional Paper 1802: Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply. Full discussion of 23 individual critical minerals, their uses, identified resources, national and global distribution, geologic overview, resource assessment, and geoenvironmental considerations are included.	Schulz, DeYoung, and others (2017)
	Professional Paper 820: Mineral resources of the United States. This publication covers all mineral resources, including the phase 2 critical minerals	Brobst and Pratt (1973)
Mineral Resources online spatial data	Interactive maps and downloadable data for regional and global analysis. Also includes databases of mineral deposits of a specific type, mineral resource assessments, and access to other geologic, geochemical, and geophysical datasets.	https://mrdata.usgs.gov/
Mineral Resources Data System (MRDS)	MRDS describes metallic and nonmetallic mineral resources throughout the world. Included data are deposit name, location, commodity, and references. Some records include deposit description, geologic characteristics, production, reserves, and resources. It includes the original MRDS and Mineral Availability System/Mineral Industry Location System (MAS/MILS) data.	https://mrdata.usgs.gov/mrds/
Commodity information	The USGS National Minerals Information Center (NMIC) publishes monthly, quarterly, and annual reports on individual commodities as well as annual statistics and information on each State and Country.	https://www.usgs.gov/centers/nmic
Geology	This data release is a compilation of State geologic maps for the conterminous United States. Some of the focus areas are based on selections of particular lithologies from this compilation (for example, phosphate, anorthosite).	Horton (2017)
	The National Geologic Map Database Project (NGMDB) is a collaborative effort primarily involving the USGS and the Association of American State Geologists (AASG). Geologic map coverages and locations for individual geologic maps are available on the National Geologic Map Database.	https://ngmdb.usgs.gov/Info/

Table 3. Data sources used to develop focus areas for data acquisition for potential domestic sources of critical minerals.—Continued

[Abbreviations: Earth MRI, Earth Mapping Resources Initiative; USGS, U.S. Geological Survey; REEs, rare earth elements; GIS, geographic information system; USMIN, USGS Mineral Deposit Database; PGEs, platinum-group elements; lidar, light detection and ranging]

Topic	Description	Reference
Geophysics	An article describing the status of U.S. magnetic data.	Drenth and Grauch (2019)
	Data release: A compilation of the locations of airborne geophysical surveys in the United States. In support of Earth MRI, suitability rankings of airborne geophysical surveys for supporting geologic studies were evaluated and determined for aeromagnetic and airborne radiometric data. The aeromagnetic suitability rankings documented by Drenth and Grauch (2019) were applied to the geophysical survey inventory based on data type, survey specifications, and data issues with 1 being the best and 5 being the least suitable. The criteria used to rank the surveys are explained in table 1 of Drenth and Grauch (2019) and described in detail in the process step of the metadata.	Johnson and others (2019)
Lidar data	Status maps and lidar data from the USGS 3D Elevation program (3DEP) and data are available online. In addition, some States have their own data available.	https://www.usgs.gov/core-science-systems/ngp/3dep/3dep-data-acquisition-status-maps
Exploration sites	Company websites, reports, and press releases	

Mineral Occurrences

Mineral occurrence data for select critical minerals are available in a series of data releases as part of the USGS Mineral Deposit Database (USMIN) project (table 3). As of May 2020, mineral occurrence data releases were available for the following phase 2 critical minerals: cobalt, lithium, rare earth elements, tin, and tungsten (Burger and others, 2018; Carroll and others, 2018; Karl and others, 2018, 2019; Bellora and others, 2019). A report by Schulz, DeYoung, and others (2017) provides national and global information on resources for 23 critical minerals—antimony (Sb), barite (barium, Ba), beryllium (Be), cobalt (Co), fluorite or fluorspar (fluorine, F), gallium (Ga), germanium (Ge), graphite (carbon, C), hafnium (Hf), indium (In), lithium (Li), manganese (Mn), niobium (Nb), platinum-group elements (PGEs), rare earth elements (REEs), rhenium (Re), selenium (Se), tantalum (Ta), tellurium (Te), tin (Sn), titanium (Ti), vanadium (V), and zirconium (Zr). A data release that complements that report includes point and polygon layers within a geodatabase that shows selected mineral resource features (deposits, mines, districts, mineral regions) for 22 minerals or mineral commodities considered critical to the economy and security of the United States as of 2017 (Labay and others, 2017). These geospatial data and the accompanying report are an update to information published in 1973 in U.S. Geological Survey Professional Paper 820, "United States Mineral Resources." For the current and full discussion of the individual critical minerals, their uses, identified resources, national and global distribution, geologic overview, resource assessment, and geoenvironmental considerations see Schulz, DeYoung, and others (2017).

Older, generally less well documented, information is available in the online Mineral Resources Data System (MRDS, https://mrdata.usgs.gov/mrds/). The MRDS describes metallic and nonmetallic mineral resources throughout the world. Data included are deposit name, location, commodity, and references. Some records include deposit description, geologic characteristics, production, reserves, and resources. The database includes the original USGS MRDS and data from Mineral Availability System/Mineral Industry Location System (MAS/MILS), the database maintained by the former U.S. Bureau of Mines; these datasets can be searched by commodity or geographic area of interest. The MRDS and MAS/MILS databases are static and no longer maintained for currency nor accuracy by the USGS. In the 1970s and 1980s, the USGS produced the Open-File Report 79–576 series—a series of preliminary province maps for many commodities that included information on deposit types, preliminary estimates of resource potential (high, medium, low), and an evaluation of the status of geologic information—such as those for REEs (Staatz and Armbrustmacher, 1981), tin (Reed and Tooker, 1980), and titanium (Tooker and Force, 1980). Many States maintain statewide databases of mineral occurrences that are available through their websites. Participating States provided data on mineral occurrences and regional expertise to the USGS to support this analysis. Selected references for each focus area are included in the tables that accompany the GIS in the accompanying data release (Dicken and Hammarstrom, 2020).

Geologic Maps

A compilation of State-scale (1:50,000- to 1:1,000,000-scale) geological maps for the conterminous United States provides preliminary data on the distribution of lithologies that could be associated with different types of deposits (Horton, 2017). References for more detailed maps used to delineate each focus area are listed in the tables in the accompanying data release (Dicken and Hammarstrom, 2020). Many of the cited geologic maps that underlie the focus areas are available through the National Geologic Map Database for viewing and, in many cases, download (https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html). Site specific and original source State geologic maps should be consulted for additional information, as not all relevant geologic maps are referenced in this report.

Geophysical Data

Geophysical data are essential for identifying the rocks and geologic structures that host many types of potential mineral deposits that are obscured under cover rocks and soils or in heavily vegetated areas. Airborne methods allow coverage of large areas, allowing characterization over wide regions that can inform land-use planning and focused studies. To date, Earth MRI efforts have focused on aeromagnetic and airborne radiometric methods because their relatively lower acquisition costs enable greater areal coverage. However, other methods such as electromagnetics and gravity methods can also be helpful in the future for certain types of deposits.

In some cases, a geophysical anomaly associated with rock types that may host mineral resources is the primary basis for defining a focus area that warrants additional study to determine the likelihood of occurrence of mineral deposits that host critical minerals. For example, radiometric data are especially valuable for identifying surficial deposits that contain thorium or potassium, such as heavy-mineral sands containing monazite, a possible REE resource, and for mapping potassic alteration associated with hydrothermal systems. Magnetic data are helpful for identifying deposits that are associated with mafic magmatic rocks such as PGE- or REE-hosting iron oxide-apatite deposits (McCafferty and others, 2019; Phillips and McCafferty, 2019). Geophysical methods also contribute basic knowledge of the three-dimensional geologic context of critical mineral resources that could only otherwise be obtained by drilling, and thus play a fundamental role in characterizing buried mineral deposits.

The quality of national aeromagnetic and airborne radiometric data coverage was compiled and ranked by Johnson and others (2019). These rankings were used to evaluate the quality of available geophysical data for each focus area. Although national coverages exist for both magnetic and radiometric data, the quality of available data for most areas is poor (typically low resolution) and inadequate for mineral exploration, indicating a strong need for new data collection. High-resolution data can provide structural and stratigraphic details that are not evident in the lower resolution data which comprise much of the data available to the public.

Geophysical methods for identifying mineral systems that could contain phase 2 critical minerals in the United States are summarized in table 4. Mineral systems and deposit types follow the classification scheme of Hofstra and Kreiner (2020). The table includes comments on the relative utility of different methods for different mineral systems and deposit types.

Elevation Data

Direct detection of critical commodities requires chemical analysis of rocks and other materials. High-resolution elevation data, such as lidar, and airborne geophysical methods do not directly detect critical commodities but are an essential part of a 21st century data infrastructure to map the mineral resource potential of critical commodities. The USGS 3D Elevation Program (3DEP) is systematically acquiring lidar data for the conterminous United States and interferometric synthetic aperture radar (IfSAR) data for Alaska.

The 3DEP dataset is a complex and rich dataset that can be processed in many ways; the most useful first-order derivative for geologic applications is the raster of the bare-earth surface. This dataset will give a precise elevation of the surface of the earth for every square meter of study area, seeing through vegetation.

The features at the surface of the earth result from a combination of physical, chemical, and biological processes. Terrain analysis of lidar data can be used to distinguish landforms that can be related to geological features associated with critical mineral deposits. The analysis of terrain can also be used a tool to make the geologic mapping process more efficient by highlighting areas where bedrock is exposed.

Differential weathering of various bedrock units is related to their differing physical and chemical properties. Landform analysis can be used to map different bedrock units. If a critical mineral deposit is related to a particular bedrock unit that weathers in a characteristic way, the imagery will clearly show the distribution of a unit. For example, in layered rock sequences, the various rock layers are easily seen on some derivative lidar images. Details from a lidar survey over the Stillwater Complex in Montana, the most important domestic source of PGEs, revealed topographic details that were previously unrecognized (Meiser, 2019).

Fractures, faults, and dikes also weather differentially. In derivative lidar images, these features show up as prominent lineaments. Their distribution is important because fractures, faults, and dikes may be the pathways for ore-forming fluids or melts that formed deposits. If the features formed subsequent to ore formation, geologists can use them to interpret discontinuities that offset mineralized rock.

Table 4. Geophysical methods for identifying mineral systems and deposit types in the United States that could contain phase 2 critical minerals.

[This table includes a general summary of geophysical methods associated with the different deposit types described in terms of “excellent,” “important,” and “helpful.” The “excellent” methods are at times capable of imaging deposits directly, whereas “helpful” methods typically are used to provide information on the geologic framework. Note that a surface expression is required for radiometric methods to be effective, electromagnetic methods are usually limited to 300- to 400-meter depth penetration, and gravity and electromagnetic methods are significantly more expensive than magnetic and radiometric methods. See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types. Abbreviations: sed, sediment; MVT, Mississippi Valley-type; sedex, sedimentary exhalative; REEs, rare earth elements; NYF, niobium-yttrium-fluorine; IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; S-R-V, skarn, replacement, or vein; PGE, platinum-group element; Cu, copper; Mo, molybdenum; Au, gold; Sn, tin; LCT, lithium-cesium-tantalum]

Mineral system	Deposit type	Magnetic methods	Radiometric methods	Gravity methods	Electromagnetic methods
Alkalic porphyry	Porphyry/skarn copper-gold	May be important for detection; excellent for geologic framework	Helpful for surface mapping	May help detection, excellent for geologic framework	Often excellent for detection; important for geologic framework
Basin brine path	Copper (sed-hosted and replacement) Uranium (unconformity) Zinc-lead (MVT and sedex)	Helpful for geologic framework	May be excellent for detection	Helpful for geologic framework	May be excellent for detection; important for geologic framework
Chemical weathering	Bauxite Nickel-cobalt laterite Regolith (ion adsorption) REEs	Helpful for geologic framework	Important for geologic framework	Helpful for geologic framework	May be excellent for detection; important for geologic framework
Climax-type	Lithocap alunite Volcanogenic beryllium or uranium Greisen Porphyry molybdenum Skarn molybdenum Pegmatite (NYF)	Important for geologic framework	Important for geologic framework	Important for geologic framework	May be excellent for detection; important for geologic framework
Hybrid peralkaline intrusion Carbonatite Basin brine path	Fluorspar (replacement)	Important for geologic framework	Important for geologic framework	Important for geologic framework	May be excellent for detection; important for geologic framework
IOA-IOCG	Iron oxide-copper-gold Iron oxide-apatite Polymetallic sulfide S-R-V	May be excellent for detection; excellent for geologic framework	Important for geologic framework	May be excellent for detection; excellent for geologic framework	May be excellent for detection; helpful for geologic framework
Lacustrine evaporite	Residual brine Lithium clay Lithium-boron zeolite	May be helpful for geologic framework	Important for geologic framework	Helpful for geologic framework	May be excellent for detection; important for geologic framework
Mafic magmatic	Nickel-copper-PGE sulfide Iron-titanium oxide	May be excellent for detection; excellent for geologic framework	Helpful for geologic framework	May be excellent for detection; excellent for geologic framework	May be excellent for detection; important for geologic framework
Magmatic REE	Peralkaline syenite/granite/rhyolite/alaskite/pegmatites Carbonatite Phosphate	May be excellent for detection;excellent for geologic framework	May be excellent for detection; excellent for geologic framework	May be excellent for detection; important for geologic framework	Helpful for geologic framework
Marine chemocline	Black shale Phosphate	May be helpful for geologic framework	May be excellent for detection; excellent for geologic framework	May be helpful for geologic framework	May be excellent for detection; excellent for geologic framework

Table 4. Geophysical methods for identifying mineral systems and deposit types in the United States that could contain phase 2 critical minerals.—Continued

[This table includes a general summary of geophysical methods associated with the different deposit types described in terms of “excellent,” “important,” and “helpful.” The “excellent” methods are at times capable of imaging deposits directly, whereas “helpful” methods typically are used to provide information on the geologic framework. Note that a surface expression is required for radiometric methods to be effective, electromagnetic methods are usually limited to 300- to 400-meter depth penetration, and gravity and electromagnetic methods are significantly more expensive than magnetic and radiometric methods. See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types. Abbreviations: sed, sediment; MVT, Mississippi Valley-type; sedex, sedimentary exhalative; REEs, rare earth elements; NYF, niobium-yttrium-fluorine; IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; S-R-V, skarn, replacement, or vein; PGE, platinum-group element; Cu, copper; Mo, molybdenum; Au, gold; Sn, tin; LCT, lithium-cesium-tantalum]

Mineral system	Deposit type	Magnetic methods	Radiometric methods	Gravity methods	Electromagnetic methods
Marine evaporite	Dissolution brine	May be helpful for geologic framework	May be excellent for detection; excellent for geologic framework	May be helpful for geologic framework	May be excellent for detection; excellent for geologic framework
Metamorphic	Graphite (amorphous-flake)	May be helpful for geologic framework	May be helpful for detection; excellent for geologic framework	May be helpful for geologic framework	May be excellent for detection; excellent for geologic framework
Meteoric recharge	Sandstone uranium	May be helpful for geologic framework	May be excellent for detection; excellent for geologic framework	May be helpful for geologic framework	May be excellent for detection; excellent for geologic framework
Placer	PGEs Ilmenite/rutile/leucoxene Monazite/xenotime Cassiterite Wolframite/scheelite	May be excellent for detection; excellent for geologic framework	May be excellent for detection; excellent for geologic framework	May be helpful for geologic framework	May be excellent for detection; excellent for geologic framework
Porphyry Cu-Mo-Au	High sulfidation gold-silver Porphyry/skarn copper or molybdenum Lithocap alunite S-R-V tungsten Greisen	May be excellent for detection; excellent for geologic framework	May be helpful for detection; excellent for geologic framework	May be excellent for detection; important for geologic framework	May be excellent for detection; important for geologic framework
Porphyry Sn	Pegmatite (LCT) Greisen Porphyry/skarn	Important for geologic framework	May be helpful for detection; excellent for geologic framework	Important for geologic framework	Important for geologic framework
Orogenic (metamorphic shear zone hydrothermal)	Graphite vein (lump)	May be helpful for geologic framework	May be helpful for detection; excellent for geologic framework	May be helpful for geologic framework	May be excellent for detection; excellent for geologic framework
Reduced intrusion-related	Graphite vein (lump)	May be helpful for geologic framework	May be helpful for detection, excellent for geologic framework	May be helpful for geologic framework	May be excellent for detection, excellent for geologic framework

Lidar data can also be used to map the form and distribution of sediments and sedimentary rock. For example, in coastal plain environments, high-resolution elevation data can be used to delineate bedforms, sedimentary facies, and related geomorphologic features. Lidar data can also be used to map fluvial landforms in sedimentary or hard rock terranes. These various features sometimes show correlations with heavy-mineral-sand or placer deposits (for example, Pirkle and others, 2013; Kirkpatrick and others, 2019). Elsewhere, some sedimentary deposits cover bedrock sources of critical commodities; mapping the features in the covering material can help interpret transport directions—critical to understanding and interpreting soil, stream sediment, and till geochemistry and facilitating use of associated databases like the National Uranium Resource Evaluation (NURE) stream sediment and the USGS National Geochemical Database.

Finally, terrain analysis can be used to locate manmade features, including abandoned mines or mining waste that contain critical mineral resources. For example, lidar data in the eastern Adirondack Mountains of northern New York help better define numerous piles of waste and mill tailings that contain REEs (Taylor and others, 2019; Walsh and others, 2020). Lidar can be used to estimate volumes of materials that could be reprocessed to produce critical minerals.

Delineation of Focus Areas

Focus areas for the phase 2 critical mineral commodities in the United States were delineated by teams of USGS geologists working with representatives from State geological surveys and other institutions. Some focus areas contain mineral deposits, prospects, and (or) occurrences of critical mineral commodity resources that are currently mined, were mined in the past, or are known but have never been recovered. Other focus areas have evidence of the presence of relevant mineral systems so are considered geologically permissive for the occurrence of critical minerals.

The preliminary work of delineating and documenting focus areas was done by regional USGS teams, compiled in a GIS database, and shared with scientists from the participating State geological surveys prior to the workshops. During the workshops, USGS scientists worked with these colleagues to refine focus areas. Workshops included breakout groups to cover multistate subregions (Northwest, Southwest, Rocky Mountain, North-Central, South-Central, Northeast, Southeast) as a way to uniformly assemble and analyze the relevant data (fig. 2). GIS experts provided support at the workshops to capture changes in realtime.

The teams considered the spatial distribution of known mineral occurrences along with the geologic systems associated with those mineral occurrences and other data. Some focus areas were based on selection of geologic map units that include a key favorable host rock type for a particular critical mineral. For example, the focus areas for Ordovician and Devonian phosphates that contain REEs were selected as the relevant geologic units on State-scale geologic maps. Other focus areas were based on generalized outlines of mining districts or mineral belts, distributions of observed occurrences, polygons of mining areas and surface features, and, in some cases, geochemical and (or) geophysical anomalies that could be associated with deposits. Some focus areas for lithium were based on outlines of watersheds using 8-digit hydrologic unit code (HUC8) boundaries. Hydrologic unit codes (HUCs) are part of the watershed boundary dataset, a hierarchical system of nested hydrologic units used to map the extent of surface waters of the United States. HUC8 watersheds typically represent subbasins, such as medium-sized river basins (Seaber and others, 1987). In some cases, a broad focus area was defined as a "parent" area that outlines the extent of the mineral system and encompasses smaller "children" areas. For example, the focus area for the chemical weathering mineral system for high-aluminum Pennsylvanian underclays encompasses nine smaller focus areas.

A template was used to document key information about each focus area and identify specific needs for new data (table 5). The template captures the rationale for delineating the focus area, the relevant mineral systems and deposit types, information on past production, and other information that supports delineation of the focus area for critical minerals. The USGS prepared preliminary versions of the focus area maps and tables that were supplemented, refined, and edited by State geological surveys.

Using Focus Areas

Focus areas and template tables for phase 2 critical mineral commodities in the United States and Puerto Rico are included in a GIS data release (Dicken and Hammarstrom, 2020).

A total of 498 focus area polygon features includes 74 areas in Alaska, 1 in Hawaii, 2 in Puerto Rico, and 421 areas in the conterminous United States (fig. 2). The size of individual focus areas is highly variable, ranging from less than 10 to 30,000 square kilometers, and dependent on the type of mineral system considered. Very large areas highlight broad regions of the country where certain mineral systems are known to occur; this does not imply that every part of the area is geologically permissive for critical minerals. These include "parent" areas that outline groups of smaller "children" areas that may represent a potential target area for new geologic mapping or other studies. About 20 percent of the focus areas are less than 200 square kilometers in size, or about the size of a 1:24,000-scale quadrangle or smaller. Other areas outline the maximum extent of large geologic features such as basins or belts of intrusive igneous rocks of a certain age.

The focus areas highlight different mineral systems, deposit types, and critical mineral commodities, all of which are included as attributes in the GIS data release

(Dicken and Hammarstrom, 2020). For example, the distribution of focus areas for two mineral systems in the conterminous United States is shown in figure 3. The figure shows locations for 23 focus areas for deposit types associated with iron oxide-apatite and iron oxide-copper-gold (IOA-IOCG) systems and 58 focus areas for deposit types associated with mafic magmatic systems. Note that these mineral systems are better depicted in some parts of the United States where information is more robust, but not as well in other areas where information is lacking. One goal of Earth MRI is to improve the geoscience data in the areas lacking detailed information, which will in turn help refine the focus areas themselves. Hence, the uneven fidelity of definition of the focus areas helps highlight those areas where more data are needed.

Focus areas for different deposit types in the placer system, for example, show that areas favorable for tungsten (wolframite/scheelite) are located in California, whereas extensive areas of potential resources for titanium (ilmenite/rutile/leucoxene) and niobium, tantalum, and REEs (monazite/xenotime), or favorable for both, lie along the eastern seaboard (fig. 4).

In addition to focus areas, major structural boundaries such as faults, sutures, or geophysical features may host buried mineral systems or parts of mineral systems that could host a variety of deposit types. The Great Lakes Tectonic Zone, for example, extends across parts of Michigan, Minnesota, South Dakota, and Wisconsin (fig. 3), and may conceal a variety of critical minerals hosted in deposit types belonging to four different mineral systems. A few examples are listed table 6 and shown on figure 3.

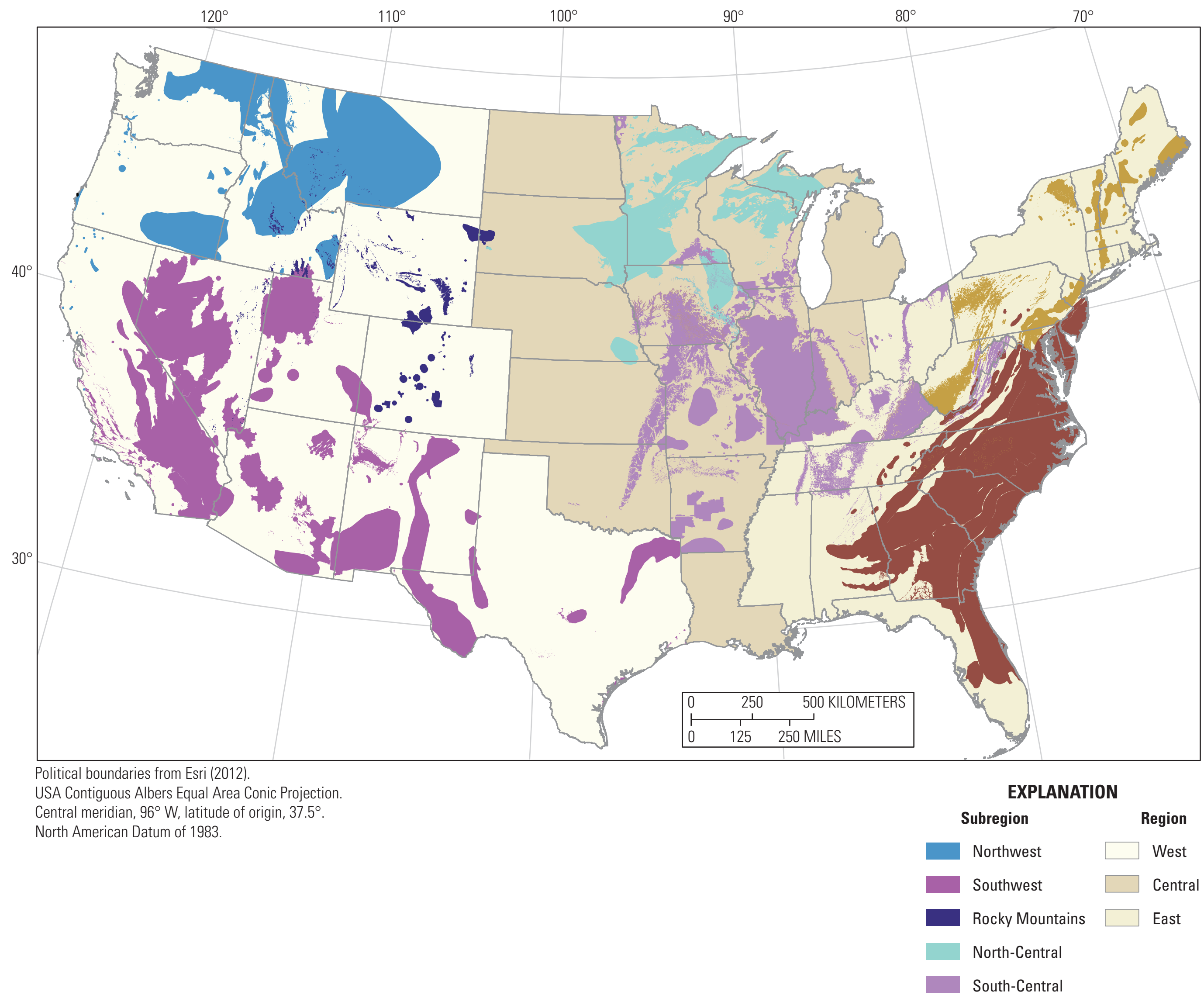


Figure 2. Map showing the distribution of focus areas in the conterminous United States for each subregion. Note that boundaries of individual focus areas are not shown.

Table 5. Factors used in the template to delineate U.S. focus areas having the potential to contain sources of critical minerals in nonfuel deposit types.

[USGS databases: ARDF, Alaska Resource Data File (https://mrdata.usgs.gov/ardf/); MRDS, Mineral Resources Data System (https://mrdata.usgs.gov/mrds/); USMIN, USGS Mineral Deposit Database (https://minerals.usgs.gov/science/mineral-deposit-database/)]

Topic	Explanation
Name of focus area	Descriptive geographic or geologic name
Region	Alaska, West, Central, East
Subregion	Northwest, Southwest, Rocky Mountain, North-Central, South-Central, Northeast, Southeast
Mineral system	Select from appendix 1
Deposit type(s)	Select from appendix 1
Commodities	Mineral commodities associated with the focus area
Identifier	A unique identifier for each focus area; some focus areas may be multipart
States	States included in the focus area
Basis for focus area	Short description of the main geologic criteria (basis) for delineating the area
Production	Yes (when), no, or unknown
Status of activity	Active mining, current or past exploration, unknown
Estimated resources	Cite, if known
Geologic maps	Estimate of the percentage of the focus area covered by geologic mapping at different scales; cite specific references if applicable
Geophysical data	Types and quality of available data (aeromagnetic, gravity, radiometric, other)
Favorable rocks and structures	Lithostratigraphic suitability for deposits; structures that may control mineralization
Deposits	Named deposits within the focus area that have identified resources or past production
Mineral occurrences	Summarized occurrences, if any, from USMIN, MRDS, ARDF, or other databases
Geochemical evidence	Stream sediment, rock, or soil indications of various commodities
Geophysical evidence	Data that may indicate buried intrusions, extensions of known mineralization, or structural controls
Evidence from other sources	If applicable
Comments	Author's general comments on the focus area
Cover thickness and description	Comment, if applicable. Otherwise, not applicable (NA)
Selected references	Short reference (authors, year)
Authors	USGS and State geological surveys
Specific new data needs	
Geologic mapping and modeling needs	List geologic mapping needs
Geophysical survey and modeling needs	List types of geophysical data needed and explain why
Lidar	Give examples of utility of lidar for the focus area

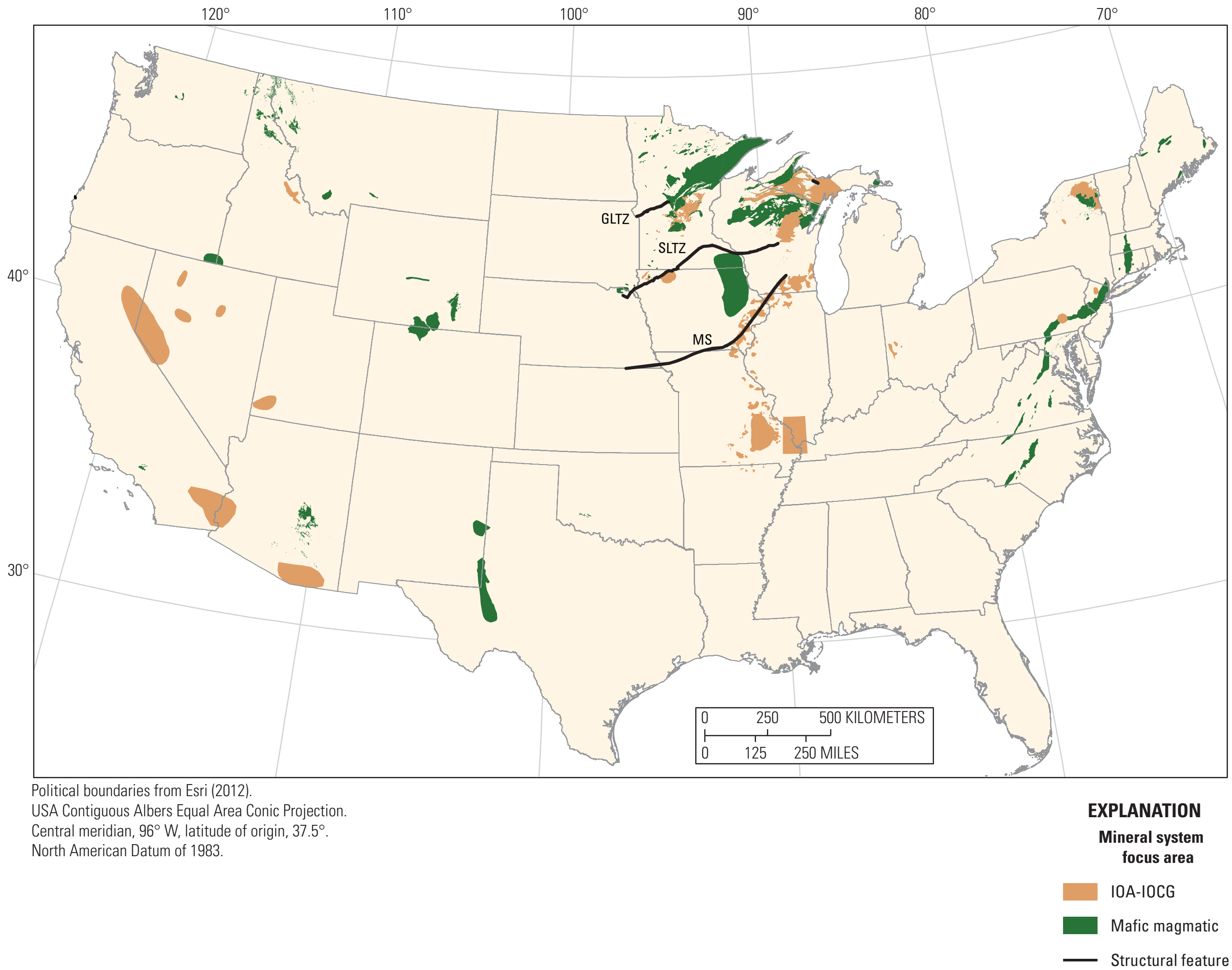
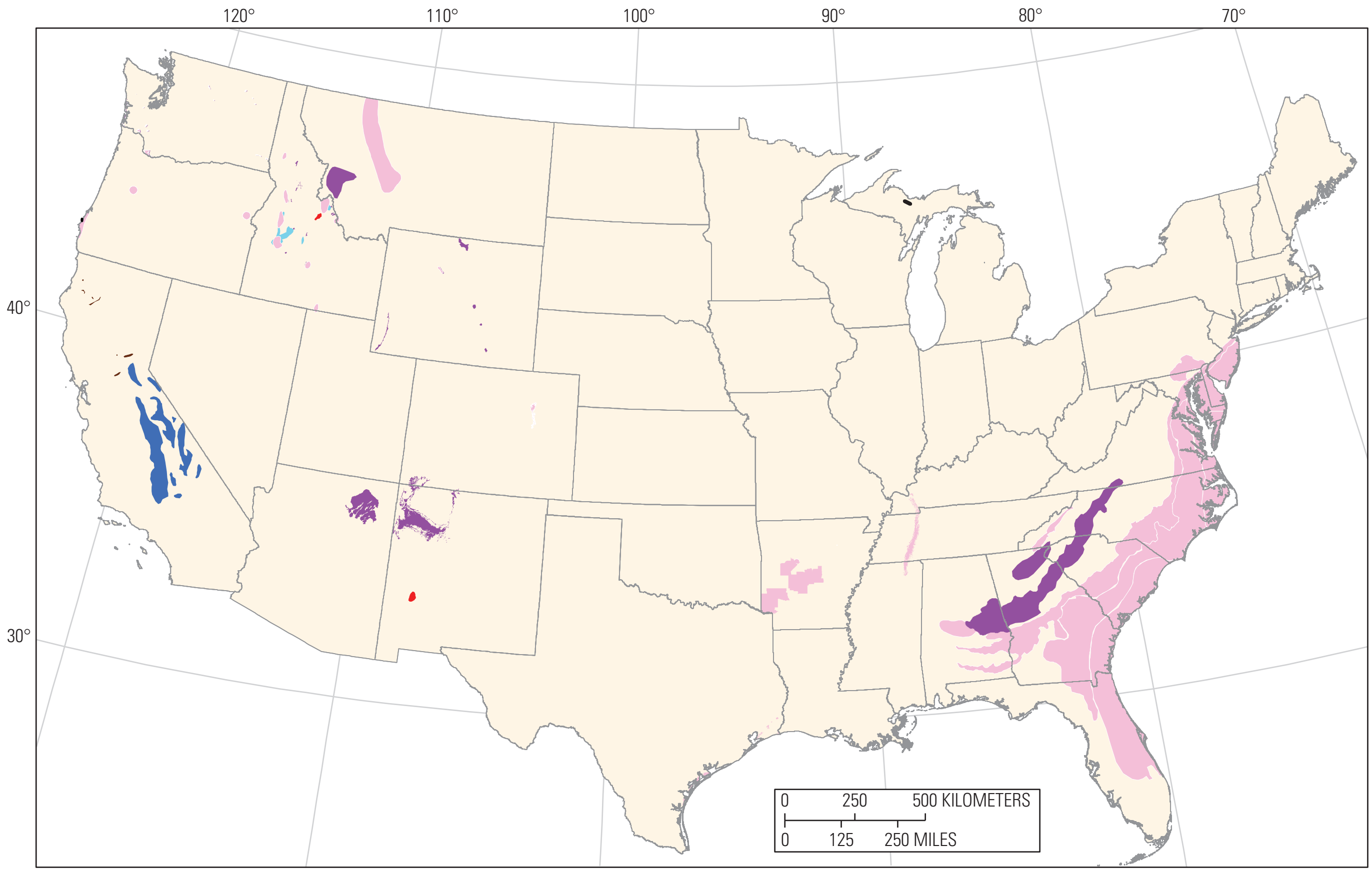


Figure 3. Map showing the distribution of focus areas for iron oxide-apatite and iron oxide-copper-gold (IOA-IOCG) and mafic magmatic mineral systems in the conterminous United States. Selected examples of structural features that may conceal or control distributions of mineral deposits in the North-Central subregion of the United States are also shown (see table 6). GLTZ, Great Lakes Tectonic Zone; SLTZ, Spirit Lake Tectonic Zone; MS, Mazatzal suture.



Political boundaries from Esri (2012).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 96° W, latitude of origin, 37.5°.
North American Datum of 1983.

EXPLANATION

Placer mineral system deposit type

- Cassiterite
- Columbite/tantalite
- Ilmenite/rutile/leucoxene
- Platinum-group elements
- Monazite/xenotime
- Wolframite/scheelite

Figure 4. Map showing the distribution of focus areas for placer systems in the conterminous United States.

Table 6. Examples of structural or geophysical features that may conceal mineral systems in the North-Central subregion of the United States.

[See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types. Abbreviations: PGE, platinum-group element; REE, rare earth element; IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; Sn, tin; LCT, lithium-cesium-tantalum]

Name of feature	State	Mineral system	Deposit type
Great Lakes Tectonic Zone	Michigan, Minnesota, South Dakota, Wisconsin	Mafic magmatic	Nickel-copper-PGE sulfide
		Magmatic REE	Peralkaline syenite/granite/rhyolite/alaskite/pegmatites
		IOA-IOCG	Iron oxide-copper-gold
		Porphyry Sn (granite-related)	Pegmatite (LCT)
Mazatzal suture	Illinois, Iowa, Kansas, Missouri, Nebraska, Wisconsin	Mafic magmatic	Nickel-copper-PGE sulfide
		Magmatic REE	Peralkaline syenite/granite/rhyolite/alaskite/pegmatites
		IOA-IOCG	Iron oxide-copper-gold
		Porphyry Sn (granite-related)	Pegmatite (LCT)
Spirit Lake Tectonic Zone	Iowa, Minnesota, Nebraska, South Dakota, Wisconsin	Mafic magmatic	Nickel-copper-PGE sulfide
		Magmatic REE	Peralkaline syenite/granite/rhyolite/alaskite/pegmatites
		IOA-IOCG	Iron oxide-copper-gold
		Porphyry Sn (granite-related)	Pegmatite (LCT)
			Porphyry/skarn

Phase 2 Critical Mineral Commodities and Associated Mineral Systems

The following sections describe the importance and mode of occurrence of the phase 2 critical mineral commodities and the mineral systems and deposit types that can host the critical minerals as either product, coproduct, or byproduct commodities in the conterminous United States, Hawaii, and Puerto Rico. The first topic in each section, “Importance to the Nation’s Economy,” includes excerpts on domestic production and use and world resources for each of the 11 critical minerals from the “Mineral Commodity Summaries 2020” (U.S. Geological Survey, 2020).

The distributions of focus areas associated with each critical mineral are shown on maps (figs. 5–14) indicating the mineral systems along with point locations for significant mineral occurrences from published data sources. Examples of focus areas for each critical mineral are listed in tables that list the mineral system, deposit types, names of selected representative focus areas, and the State(s) in which the focus areas occur (tables 7–16). The mineral systems and deposit types that are most likely to host new or additional resources for the critical mineral in the reasonably foreseeable future are noted with an asterisk in the tables. However, acquisition of new data may show that other systems or deposit types host critical minerals as byproducts in less conventional deposit types.

Maps were constructed from the GIS in the data release (Dicken and Hammarstrom, 2020) by selecting each focus area for the particular critical mineral commodity listed in the attribute field “Commodities.” All focus areas containing that critical mineral commodity were plotted by mineral system. Therefore, the maps represent areas of the country where the critical mineral commodity could be present as the primary commodity or as a potential byproduct or coproduct of other principal commodities. For example, “Porphyry Cu-Mo-Au” systems include the deposit type “S-R-V-tungsten” (tungsten skarns, replacements, and veins). Tungsten skarns are the major source of global tungsten; 55 focus areas are delineated for this deposit type. Tungsten also occurs as a known or potential byproduct in other mineral systems where the principal commodity is molybdenum or tin.

Aluminum (Bauxite, Alunite, Other)

Importance to the Nation’s Economy

The following two subsections describing factors indicating the importance of aluminum to the Nation’s economy are quoted from the “Mineral Commodity Summaries 2020” (U.S. Geological Survey, 2020, p. 30–31).

> *Domestic Production and Use:* In 2019, the quantity of bauxite consumed was estimated to be 5.1 million tons, 30% more than that reported in 2018, with an estimated value of about $162 million. About 73% of

the bauxite was refined by the Bayer process for alumina or aluminum hydroxide, and the remainder went to products such as abrasives, cement, chemicals, proppants, refractories, and as a slag adjuster in steel mills. Two domestic Bayer-process refineries with a combined alumina production capacity of 1.7 million tons per year produced an estimated 1.6 million tons in 2019, slightly more than that in 2018. One other refinery with 2.3 million tons per year of capacity that had been on care-and-maintenance status since 2016 was permanently shut down in December. About 66% of the alumina produced went to primary aluminum smelters, and the remainder went to nonmetallurgical products, such as abrasives, ceramics, chemicals, and refractories.

World Resources: Bauxite resources are estimated to be 55 billion to 75 billion tons, in Africa (32%), Oceania (23%), South America and the Caribbean (21%), Asia (18%), and elsewhere (6%). Domestic resources of bauxite are inadequate to meet long-term U.S. demand, but the United States and most other major aluminum-producing countries have essentially inexhaustible subeconomic resources of aluminum in materials other than bauxite.

Mode of Occurrence

The principal ore for aluminum is bauxite, a naturally occurring, heterogeneous material composed primarily of one or more aluminum hydroxide minerals, plus various mixtures of silica, iron oxide, titanium dioxide, aluminosilicate, and other impurities in minor or trace amounts (U.S. Geological Survey, 2015). Gibbsite and the polymorphs boehmite and diaspore are aluminum hydroxide minerals found in bauxites. Bauxite typically occurs as a residual soil produced by intense weathering. Historically, bauxite was produced in the United States, especially during World War II. Since 1988, only small amounts of bauxite have been produced domestically (exact amounts are proprietary) in Alabama, Arkansas, and Georgia (fig. 5). The Alabama and Georgia deposits are more accurately described as bauxitic clay rather than true bauxite (U.S. Geological Survey, 2020). Domestic resources of bauxite are considered inadequate to meet long-term U.S. demand. Globally, bauxite is a major source of another critical mineral, gallium. Identification of domestic sources of bauxite might also identify potential new sources of gallium.

Potential non-bauxite aluminum resources include the mineral alunite, $KAl_3(SO_4)_2(OH)_6$, that typically forms in lithocaps associated with porphyry copper and Climax-type molybdenum deposits, and in some gold-silver deposits. Other non-bauxite sources of aluminum include high-aluminum clay, anorthosite and nepheline syenite, and the mineral dawsonite. Dawsonite, $NaAlCO_3(OH)_2$, occurs in oil shales in the Green River Formation in the Piceance basin in Colorado and Utah. Aluminum could potentially be recovered from aluminous phosphate in leached zones that overlie commercial phosphate deposits in Florida and from leachates from argillically altered rocks in porphyry copper mine waste (Tooker, 1980). Although the grades of many of these non-bauxite types of deposits and occurrences are low, the large tonnages of material that could be available for processing suggest that they could represent future domestic aluminum resources if economically feasible extraction and economic incentives were available.

Mineral Systems for Aluminum Resources

Four mineral systems can host different types of aluminum resources (fig. 5). Table 7 lists examples of focus areas for different mineral systems and deposit types throughout the conterminous United States, Hawaii, and Puerto Rico.

Chemical Weathering

Chemical weathering systems form laterites in tropical climates under stable conditions in areas of low relief where meteoric water transports chemical constituents through the vadose (unsaturated) zone. Chemical traps, such as redox and pH gradients, and (or) water table fluctuations lead to potentially economic concentrations of aluminum and other critical minerals. The source rock undergoing these processes determines the mineral or element concentrated. In the case of bauxite, the source rocks are highly variable, such as basalt, granite, syenite, schist, slate, clay, sandstone, and shale. Parent materials for bauxites are less important than the degree of weathering of feldspars and other rock-forming minerals that result in highly aluminous rocks (Patterson, 1967).

Focus areas consist of bauxite occurrences, mining districts, and areas of favorable geology and past production. Historically, bauxite was mined, along with kaolin, from deposits associated with sands and limestones in the central and southeastern United States (fig. 5). In Arkansas, bauxite was mined until 1982 from an intensely weathered nepheline syenite complex. Geochemical analyses of bauxite and associated rocks from central Arkansas, historically the most significant metallurgical grade bauxite district in the United States, indicate that they lack the enrichments in rare earth elements, gallium, and scandium that are present as byproducts in bauxites in some other parts of the world (Van Gosen and Choate, 2019).

Ferruginous bauxites occur in laterites formed by intense weathering of Miocene basaltic rocks in northwestern Oregon and southwestern Washington. The bauxites are relatively low-grade ores (about 35 weight percent Al_2O_3). The bauxites were mapped, drilled, and characterized in the 1940s but never developed (Libbey and others, 1945). High rainfall promotes intense weathering of basaltic rocks on the Hawaiian Islands of Maui and Kauai, where Patterson (1971) mapped the distribution of ferruginous bauxite and evaluated their potential as large volume, low-grade aluminum resources. The

Hawaiian deposits have never been mined; they are similar to the deposits in the Pacific northwest and are enriched in titanium and iron.

High-aluminum Pennsylvanian clays are widespread in clays associated with coal-bearing intervals in the eastern and central United States. These clays are referred to as underclays, fireclays, tonsteins, Bolivar clays, and other clays in stratigraphic units associated with coals in Pennsylvanian cyclothems. Although they have never been mined for aluminum, these clays represent a potential aluminum resource as well as a potential source of lithium and REEs and possibly other critical minerals. Detailed geochemical data are needed to assess the potential aluminum resources associated with these clays.

Magmatic REE

Magmatic REE systems encompass suites of mantle-derived peralkaline and alkaline rocks, including nepheline syenite. The mineral nepheline, $Na_3K(Al_4Si_4O_{16})$, has been shown to represent an unconventional source of both aluminum and potassium (for example, Samantray and others, 2019). The largest bauxite district in the United States, in Arkansas, formed from deep weathering of nepheline syenite.

Wind Mountain, in the Cornudas Mountains of New Mexico, is a laccolith of porphyritic nepheline syenite cut by dikes and sills of syenite, nepheline syenite, and phonolite that host a variety of REEs and other minerals (McLemore and Guilinger, 1993; McLemore and others, 1996). The area has been explored in the past for both nepheline syenite and REEs, but to date no production has occurred.

Porphyry Cu-Mo-Au and Climax-Type

Large-tonnage, low-grade replacement deposits in hydrothermally altered rhyolitic to dacitic volcanic rocks associated with both Cu-Mo-Au and Climax-type porphyry deposits are a potential source of aluminum from alunite. In general, according to Hall (1978) an alunite body should contain at least 90 million metric tons (Mt) having a content of at least 30 percent alunite to be considered potentially minable. Hydrothermal alteration of calc-alkaline volcanic rocks at Blawn Mountain, Utah, formed an alunite deposit that is projected to start up in 2020 as an open pit mine to produce potash and alumina (SOPerior Fertilizer Corp., 2019). Alunite veins near Marysvale, Utah, were investigated as possible sources of aluminum in the past. Since 1970, large deposits of low-grade alunitic rock in the southern Wah Mountains of Beaver County, Utah, and in epithermal deposits in Nevada and other western States have been documented, but no development has occurred (Vikre and Henry, 2011; Vikre and others, 2015). Large deposits of quartz-alunite rock and associated kaolinite, sericite, pyrophyllite, and other alteration minerals on the Cerro La Tiza highland southwest of San Juan, Puerto Rico, represent large, but submarginal resources (Bawiec, 1999).

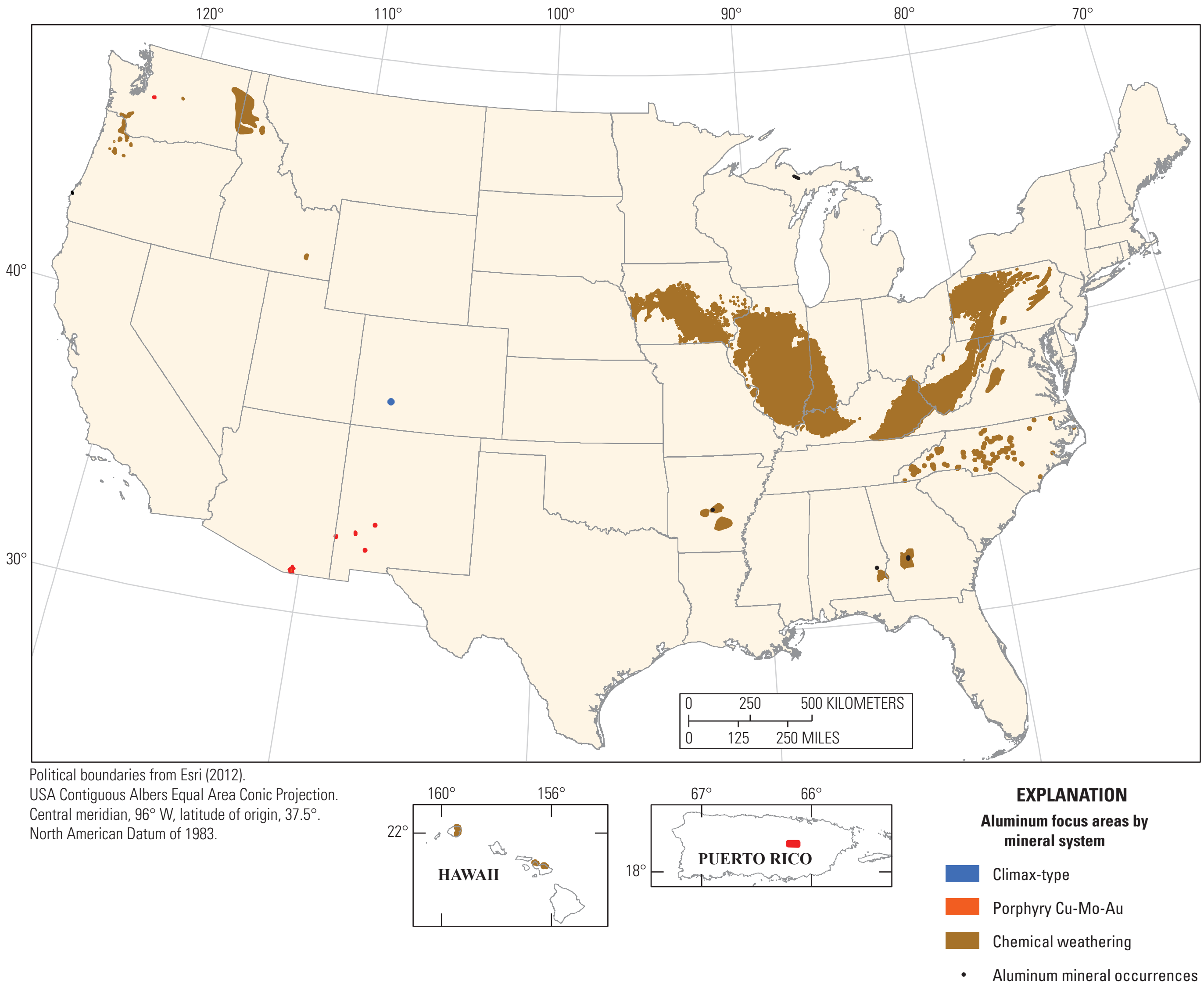


Figure 5. Map showing focus areas and mineral occurrences for aluminum resources in the conterminous United States, Hawaii, and Puerto Rico. Mineral occurrences represent areas of historical bauxite production (Mineral Resources Data System, https://mrdata.usgs.gov/mrds/). Cu, copper; Mo, molybdenum; Au, gold.

Table 7. Examples of mineral systems, deposit types, and focus areas for potential aluminum resources in the conterminous United States, Hawaii, and Puerto Rico.

[*, mineral systems and deposit types that are most likely to represent significant sources of aluminum. See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types. Abbreviations: Fm, Formation; Gp, Group; Mtn., Mountain; Cu, copper; Mo, molybdenum; Au, gold]

Mineral system	Deposit type	Focus area	State
Chemical weathering*	Bauxite*	Hawaii bauxite	Hawaii
		Southwest Washington bauxite	Oregon, Washington
		Arkansas bauxite	Arkansas
		Alabama bauxite	Alabama
	Clay	West Virginia Pottsville Fm underclays	West Virginia
		Iowa Lower Cherokee Gp underclays	Iowa, Missouri, Nebraska
		North Carolina Fireclays	Georgia, North Carolina, South Carolina
Climax-type	Lithocap alunite	Red Mountain Colorado	Colorado
		Pine Grove-Blawn Mtn.-Broken Ridge-Pink Knolls	Utah
Porphyry Cu-Mo-Au	Lithocap alunite	White River	Washington
		Puerto Rico alunite	Puerto Rico
		Alum Mountain	New Mexico
		Red Mountain Arizona	Arizona

Cobalt

Importance to the Nation's Economy

The following two subsections describing factors indicating the importance of cobalt to the Nation's economy are quoted from the "Mineral Commodity Summaries 2020" (U.S. Geological Survey, 2020, p. 50–51).

> *Domestic Production and Use:* In 2019, the nickel-copper Eagle Mine in Michigan produced cobalt-bearing nickel concentrate. In Missouri, a company built a flotation plant and produced nickel-copper-cobalt concentrate from historic mine tailings. Most U.S. cobalt supply comprised imports and secondary (scrap) materials. Approximately six companies in the United States produced cobalt chemicals. About 46% of the cobalt consumed in the United States was used in superalloys, mainly in aircraft gas turbine engines; 9% in cemented carbides for cutting and wear-resistant applications; 14% in various other metallic applications; and 31% in a variety of chemical applications. The total estimated value of cobalt consumed in 2019 was $400 million.
>
> *World Resources:* Identified cobalt resources of the United States are estimated to be about 1 million tons. Most of these resources are in Minnesota, but other important occurrences are in Alaska, California, Idaho, Michigan, Missouri, Montana, Oregon, and Pennsylvania. With the exception of resources in Idaho and Missouri, any future cobalt production from these deposits would be as a byproduct of another metal. Identified world terrestrial cobalt resources are about 25 million tons. The vast majority of these resources are in sediment-hosted stratiform copper deposits in Congo (Kinshasa) and Zambia; nickel-bearing laterite deposits in Australia and nearby island countries and Cuba; and magmatic nickel-copper sulfide deposits hosted in mafic and ultramafic rocks in Australia, Canada, Russia, and the United States. More than 120 million tons of cobalt resources have been identified in manganese nodules and crusts on the floor of the Atlantic, Indian, and Pacific Oceans.

Mode of Occurrence

Cobalt occurs in a variety of minerals including sulfides, arsenides, and oxyhydroxide minerals. In the United States, cobalt could be derived as a byproduct from mineral deposits that primarily produce other metals, including nickel (Ni), copper, zinc, and lead. Descriptions of more than 60 mineral regions, mines, and mineral deposits within the United States and its territories that are reported to contain enrichments of cobalt (Co) were included in a data release by Burger and others (2018). They reported only mined deposits and exploration prospects with past production, or resource and reserve estimates of 1,000 metric tons (t) or more of cobalt. Most of the world's cobalt is produced from sediment-hosted Cu-Co deposits, Ni-Co laterites, and magmatic sulfide deposits (Slack and others, 2017).

Mineral Systems for Cobalt Resources

Focus areas that may contain cobalt were considered using eight mineral systems (fig. 6). Table 8 lists examples of focus areas for different mineral systems and deposit types throughout the conterminous United States, and Puerto Rico.

Arsenide

Arsenide mineral systems form in continental rifts where deep-seated, oxidized, metal-rich brines ascend to shallow levels where a reduction of fluids by organic material may precipitate a variety of native elements, arsenides, and sulfide minerals (Hofstra and Kreiner, 2020). The deposits are known as five-element veins characterized by silver-, arsenic-, nickel-, bismuth-, and cobalt-bearing minerals. Significant deposits of this type include Cobalt, Ontario; Bou Azzer, Morocco; Kongsberg, Norway; Jáchymov, Czech Republic; Schneeberg, Germany; and Batopilas, Mexico (Scharrer and others, 2019; Lefebure, 1996). The Black Hawk Mining District in southwestern New Mexico is the only significant example of this mineral system recognized in the United States. The district was first developed in the 1880s for silver. The deposits are fissure veins containing nickel, cobalt, and silver in a carbonate gangue; some veins are uraniferous (Gillerman and Whitebread, 1956). Chemical analyses of samples from some of the localities that had anomalous radioactivity reported up to about 0.5 weight percent cobalt, 4 weight percent nickel, and more than 8 weight percent silver (Gillerman and Whitebread, 1956). The deposits were drilled for uranium and examined intermittently in the 1950s to 1970s, with no sustained development (Santa Fe Gold Corp., 2018). Santa Fe Gold Corporation acquired the claims in the district in 2019 with plans to develop the Black Hawk Alhambra Silver Mines Complex (Santa Fe Gold Corp., 2019).

Basin Brine Path

Cobalt can occur in copper or zinc-lead deposits that form in basin brine path mineral systems where cobalt-bearing brine encounters reduced sulfur species and precipitates ore minerals. Most of the world's cobalt comes from sediment-hosted stratiform copper deposits in Africa, where cobalt is produced as a byproduct of copper mining. Although these deposit types exist in the United States, few are known to contain significant cobalt resources. Some Mississippi Valley-type (MVT) and sedimentary exhalative (sedex) zinc-lead deposits also produce byproduct cobalt.

The Black Butte (Sheep Creek) focus area in the Smith River Mining District, Montana, hosts the recently permitted Black Butte sediment-hosted copper-silver-gold-cobalt deposit (Graham and others, 2012). The deposit contains several thousand metric tons of cobalt resources (Sandfire Resources America, Inc., 2020; Winckers and others, 2013). However, metallurgical testing indicated that byproduct silver, gold, and cobalt are presently not economically recoverable using the froth flotation method to produce a copper concentrate. Nevertheless, the focus area represents a potential domestic cobalt resource.

Although most MVT deposits are cobalt-poor, cobalt was produced as a byproduct of lead and zinc mining in the Southeast Missouri MVT districts (Slack and others, 2017). The focus area for the Southeast Missouri MVT districts includes the Fredricktown cobalt district, Old lead belt, Mine La Motte, Washington County barite district, Indian Creek Mine, Viburnum Trend, and the Annapolis Mine areas. Cobalt concentrations in other MVT deposits have not been well documented and may represent potential domestic cobalt resources in ores or mine waste.

Chemical Weathering

Nickel-cobalt laterites develop in humid tropical climates where intense weathering of ultramafic bedrock enriches residual soil and weathered rocks in nickel, cobalt, scandium, and sometimes PGEs. These laterites commonly form layers with ore zones up to 40 meters thick over weathered ultramafic rocks (Slack and others, 2017).

Focus areas for chemical weathering systems that could host cobalt resources include laterites in northern California and southern Oregon and nickel-cobalt laterites in western Puerto Rico. Cobalt-bearing supergene manganese deposits in the Ouachita area of Arkansas and Oklahoma and manganese deposits throughout the Valley and Ridge Province of the eastern United States represent other focus areas for potential cobalt resources. Focus areas outline belts of known manganese occurrences.

Iron Oxide-Apatite and Iron Oxide-Copper-Gold (IOA-IOCG)

Iron oxide-apatite (IOA) and iron oxide-copper-gold (IOCG) mineral systems form in subduction- and rift-related tectonic settings in a variety of Proterozoic to Phanerozoic magmatic belts around the world (Hofstra and others, 2016). IOCG deposits typically form peripheral to IOA systems at lower temperatures (Barton, 2014). The IOCG-silver-uranium-rare earth element-cobalt-nickel (IOCG-Ag-U-REE-Co-Ni) class of mineral deposits is globally important as a major source of copper, gold, and in some cases, other commodities that include cobalt.

Focus areas for IOA-IOCG deposits include outlines of known IOA-IOCG belts as well as permissive lithologies selected from geologic map units, mining districts, and locations of known deposits.

In the United States, the Idaho cobalt belt represents an important primary source of cobalt in an IOCG deposit. The Idaho cobalt belt includes the Jervois Mining's Idaho Cobalt Operations project, slated to begin production 2021, with measured and indicated resources of 5 Mt of ore with an average grade of 0.44 percent cobalt along with copper, gold, and silver (Foo and others, 2017; Jervois Mining Limited, 2019). The project area encompasses three zones including the historical Blackbird Mine. Focus areas in Idaho, as well as other potential IOCG areas in the United States, represent potential domestic sources of cobalt, pending further study.

IOA and IOCG deposits also occur in the Mesoproterozoic rocks of the Midcontinent region of the conterminous United States (Day and others, 2016; Slack and others, 2017; Mercer and others, 2020). As described by Hagni and Brandom (1989), the Boss (Bixby) deposit in the Saint Francois Mountains of southeast Missouri contains cobaltite and cobalt-bearing pyrite and would be a resource if developed. The Boss deposit is hosted in Mesoproterozoic rhyolitic and mafic- to intermediate-composition volcanic rocks. The deposit is reported to contain 40 Mt of 0.83 weight percent of copper, 18 weight percent iron, and 0.035 weight percent cobalt (Jones, 1974).

Mafic Magmatic

Ni-Cu(-Co-PGE) sulfide deposits hosted in mafic and ultramafic igneous rocks can contain significant cobalt (Naldrett, 2004, p. 307–372; Eckstrand and Hulbert, 2007). Cobalt occurs as a byproduct in conduit- and contact-type Ni-Cu-PGE deposits in Michigan and Minnesota. The Eagle Mine in Michigan is a conduit-type Ni-Cu-PGE deposit. Conduit-type Ni-Cu-PGE sulfide deposits are defined as magmatic sulfide mineralization restricted to small- to medium-sized mafic and (or) ultramafic irregularly shaped tube-like intrusions or dikes that served as pathways for flow-through of magnesium-rich basaltic magmas (Schulz and others, 2014). In 2016, the Eagle Mine produced nickel concentrate containing 24,114 t of nickel and an estimated 690 t of cobalt. Contact-type Ni-Cu-PGE magmatic sulfide deposits (Zientek, 2012) are exemplified by the large, mainly disseminated sulfide deposits that occur along the basal contact of the Duluth Complex in Minnesota where magmas intruded and incorporated older sulfur-rich country rock. Duluth Complex contact-type deposits have potential for byproduct cobalt. Negligible amounts of cobalt are present in nickel sulfide at the Stillwater PGE mine in Montana (Zientek and others, 2017). Focus areas include all known areas where the geology is broadly permissive for mafic magmatic mineral systems.

Marine Chemocline

Marine chemocline systems include black shales, upwelling-type phosphate deposits and iron-manganese deposits, such as “bathtub-ring” deposits (Force and others, 1999). The sedimentary manganese deposits in the Batesville district of Arkansas were mined starting before 1900 and were drilled and characterized by the U.S. Bureau of Mines in the 1950s (Stroud and others, 1981). Recent geochemical analyses have shown that the Arkansas manganese deposits are enriched in cobalt and warrant further study as potential cobalt resources (Douglas Hanson, Arkansas Geological Survey, written commun., 2019).

Porphyry Cu-Mo-Au

Cobalt is not typically associated with porphyry Cu-Mo-Au systems; however, elevated cobalt is reported for some deposits. Process waters, tailings, and waste rock at the Chino deposit in New Mexico, for example, are known to contain elevated cobalt (Phillip and Myers, 2003). Future recovery of cobalt and other critical minerals from waste materials at active or abandoned porphyry copper deposits may be possible should economically viable technologies for cobalt recovery be developed.

Volcanogenic Seafloor

Volcanogenic seafloor systems form in spreading centers and back arc basins where convection of seawater through hot igneous rocks forms an ore fluid that carries a variety of base metals, including cobalt. The undeveloped Bald Mountain copper-zinc sulfide deposit in the Munsungun region of Maine is an example of this type of mineral system. Trace element analyses of massive sulfide ores from Bald Mountain show that cobalt concentrations are variable within different stages of mineralization with maximum cobalt concentrations of 2,000 parts per million (ppm) cobalt in stage IV pyrite-rich veins and replacements (Slack and others, 2003).

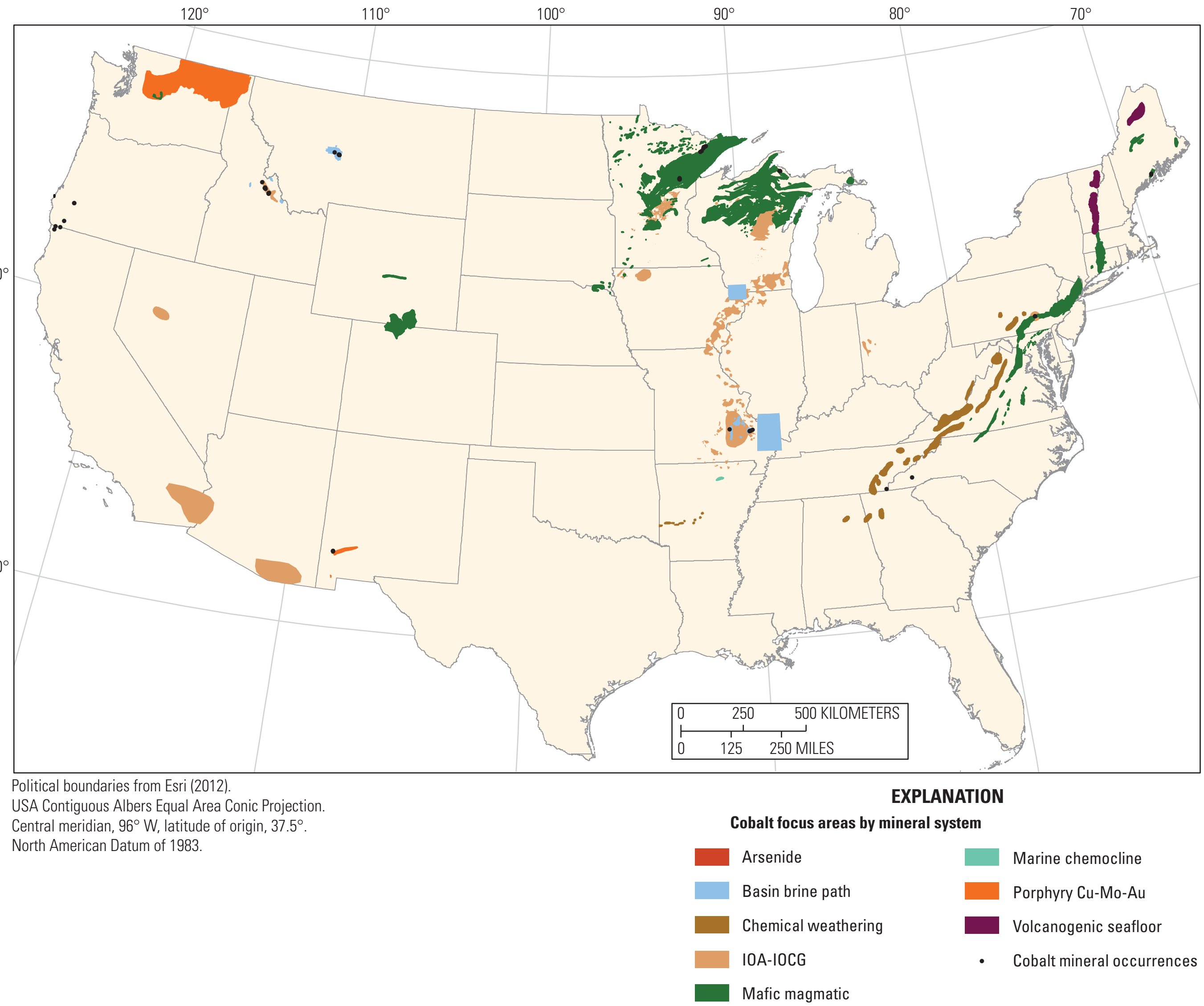


Figure 6. Map showing focus areas and significant mineral occurrences for cobalt resources in the conterminous United States. Mineral occurrences include only mined deposits and exploration prospects with past production, or resource and reserve estimates of 1,000 metric tons or more of cobalt (Burger and others, 2018). IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; Cu, copper; Mo, molybdenum; Au, gold.

Table 8. Examples of mineral systems, deposit types, and focus areas for potential cobalt resources in the conterminous United States and Puerto Rico.

[*, mineral systems and deposit types that are most likely to represent significant sources of cobalt. See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types. Abbreviations: sed; sediment; CAMP, Central Atlantic magmatic province; MVT, Mississippi Valley-type; sedex, sedimentary exhalative; Ni, nickel; Co, cobalt; IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; PGE, platinum-group element; IA, Iowa; Cu, copper; Mo, molybdenum; Au, gold]

Mineral system	Deposit type	Focus area	State
Arsenide	Five-element veins	Black Hawk Mining District	New Mexico
Basin brine path	Copper (sed-hosted and replacement)	Black Butte (Sheep Creek)	Montana
		CAMP event - Culpeper Basin	Maryland, Virginia
	Zinc-lead (MVT and sedex)	Southeast Missouri MVT districts	Missouri
Chemical weathering	Nickel-cobalt laterite	California-Oregon laterites	California, Oregon
		Puerto Rico Ni-Co laterite	Puerto Rico
	Supergene manganese	Ouachita manganese-cobalt district	Arkansas, Oklahoma
IOA-IOCG*	Iron oxide-copper-gold*	Idaho Cobalt District	Idaho
	Skarn iron	Cornwall	Pennsylvania
Mafic magmatic*	Nickel-copper-PGE sulfide*	Midcontinent Rift large mafic intrusions	Minnesota, Wisconsin
		Otter Creek complex and related IA intrusions	Iowa
		Maryland Ni-Co-Cu sulfides	Maryland, Pennsylvania
		Moxie Pluton	Maine
Marine chemocline	Iron-manganese	Batesville cobalt-manganese district	Arkansas
Porphyry Cu-Mo-Au	Porphyry copper	Tyrone-Chino-Hillsboro porphyry copper deposits	New Mexico
Volcanogenic seafloor	Polymetallic sulfide	Munsungun Region	Maine

Graphite

Importance to the Nation's Economy

The following two subsections describing factors indicating the importance of graphite to the Nation's economy are quoted from the "Mineral Commodity Summaries 2020" (U.S. Geological Survey, 2020, p. 72–73).

> *Domestic Production and Use:* In 2019, natural graphite was not produced in the United States; however, approximately 95 U.S. firms, primarily in the Great Lakes and Northeastern regions and Alabama and Tennessee, consumed 52,000 tons valued at an estimated $44 million. The major uses of natural graphite were brake linings, lubricants, powdered metals, refractory applications, and steelmaking. During 2019, U.S. natural graphite imports were an estimated 58,000 tons, which were about 65% flake and high-purity, 34% amorphous, and 1% lump and chip graphite.
>
> *World Resources:* Domestic resources of graphite are relatively small, but the rest of the world's inferred resources exceed 800 million tons of recoverable graphite.

Mode of Occurrence

Graphite ores are classified as "amorphous" (microcrystalline), and "crystalline" ("flake" or "lump or chip") on the basis of the ore characteristics such as crystallinity, grain-size, and morphology (Robinson and others, 2017). All graphite deposits that are currently in production formed by metamorphism of carbonaceous sedimentary rocks. Amorphous graphite forms by thermal metamorphism of coal. Flake graphite is mined from carbonaceous metamorphic rocks, and lump or chip graphite is mined from veins in high-grade metamorphic regions (Robinson and others 2017).

Mineral Systems for Graphite Resources

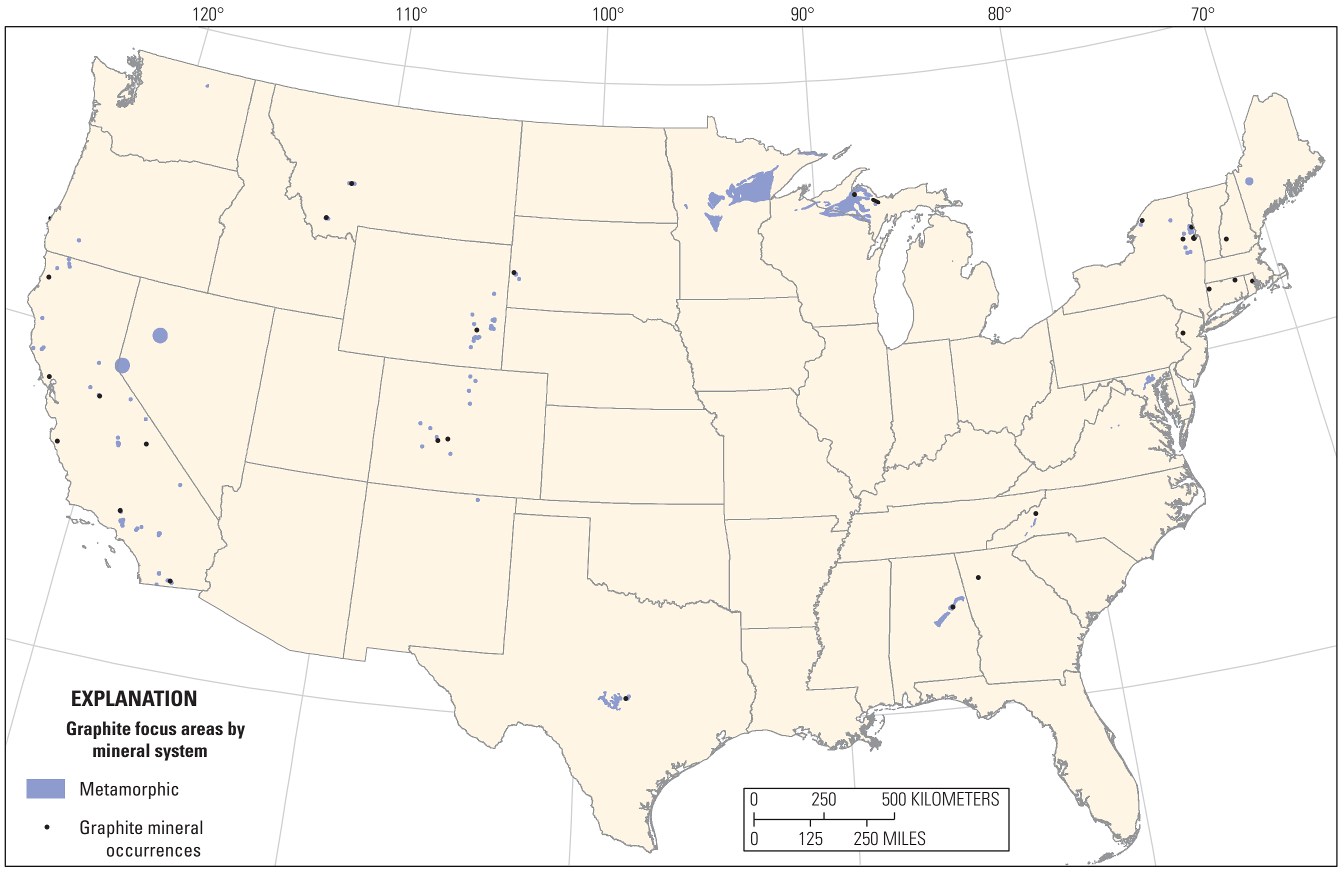
Economic concentrations of graphite are only found in metamorphic mineral systems. Historically, graphite was produced in Alabama, California, New York, Texas, and other States throughout the country. The Graphite Creek Mine in Alaska, the largest flake graphite deposit in the United States, was under construction in 2019.

The Alabama graphite belt focus area encompasses several mining districts that produced flake graphite from Neoproterozoic to lower Paleozoic graphitic schist of the Higgins Ferry Group. Westwater Resources, Inc.'s Coosa

Graphite Project in Alabama includes a battery materials production facility and the Coosa graphite deposit (3.5 Mt of contained graphite), which is expected to begin mining graphite feedstock in 2028 (Westwater Resources, Inc., 2019). The Coosa deposit and graphite deposits in the Alabama graphite belt also contain vanadium, another critical mineral (Pallister and Thoenen, 1948; Westwater Resources, Inc., 2018).

Recent increase in demand prompted grassroots exploration (mapping, sampling, and drilling) for graphite in Nevada during the past decade. The Chedic graphite property near Carson City, Nevada, which operated in the early 1900s, was drilled in 2018, with problematic drilling results (Global Li-Ion Graphite Corp., 2019). Graphite-bearing lithologies (andalusite schist) at the Grumpy Lizard graphite property near Reno were sampled in 2015 (Matica Enterprises Inc., 2015). No further activity has taken place at either property.

Other focus areas outline known historical graphite mining areas and areas of known graphitic shale. Deposits in Michigan and Rhode Island produced amorphous graphite; other areas represent potential resources for flake (crystalline) graphite (fig. 7). Table 9 lists examples of focus areas throughout the conterminous United States.



Political boundaries from Esri (2012).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 96° W, latitude of origin, 37.5°.
North American Datum of 1983.

Figure 7. Map showing focus areas and selected mineral occurrences for graphite resources in the conterminous United States. Mineral occurrences from Labay and others (2017).

Table 9. Examples of focus areas for potential graphite resources in metamorphic systems in the conterminous United States.

[See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types.]

Deposit type	Focus area	State
Graphite	Alabama graphite belt	Alabama
	Central and southern California graphite	California
	Rocky Mountain graphite	Colorado, South Dakota, Wyoming
	Nevada graphite Grumpy Lizard	Nevada
	New Mexico graphite	New Mexico
	Glens Falls and Ogdensburg quadrangles	New York
	Central Texas graphite	Texas

Lithium

Importance to the Nation's Economy

The following two subsections describing factors indicating the importance of lithium to the Nation's economy are quoted from the "Mineral Commodity Summaries 2020" (U.S. Geological Survey, 2020, p. 98–99).

> *Domestic Production and Use:* The only lithium production in the United States was from a brine operation in Nevada. Two companies produced a wide range of downstream lithium compounds in the United States from domestic or imported lithium carbonate, lithium chloride, and lithium hydroxide. Domestic production data were withheld to avoid disclosing company proprietary data.
>
> Although lithium markets vary by location, global end-use markets are estimated as follows: batteries, 65%; ceramics and glass, 18%; lubricating greases, 5%; polymer production, 3%; continuous casting mold flux powders, 3%; air treatment, 1%; and other uses, 5%. Lithium consumption for batteries has increased significantly in recent years because rechargeable lithium batteries are used extensively in the growing market for portable electronic devices and increasingly are used in electric tools, electric vehicles, and grid storage applications. Lithium minerals were used directly as ore concentrates in ceramics and glass applications.
>
> *World Resources:* Owing to continuing exploration, identified lithium resources have increased substantially worldwide and total about 80 million tons. Lithium resources in the United States—from continental brines, geothermal brines, hectorite, oilfield brines, and pegmatites—are 6.8 million tons. Lithium resources in other countries have been revised to 73 million tons. Lithium resources, in descending order, are: Bolivia, 21 million tons; Argentina, 17 million tons; Chile, 9 million tons; Australia, 6.3 million tons; China, 4.5 million tons; Congo (Kinshasa), 3 million tons; Germany, 2.5 million tons; Canada and Mexico, 1.7 million tons each; Czechia, 1.3 million tons; Mali, Russia, and Serbia, 1 million tons each; Zimbabwe, 540,000 tons; Brazil, 400,000 tons; Spain, 300,000 tons; Portugal, 250,000 tons; Peru, 130,000 tons; Austria, Finland and Kazakhstan, 50,000 tons each; and Namibia, 9,000 tons.

Mode of Occurrence

More than one-half of the world's supply of lithium is produced from closed-basin brines. Other lithium sources include pegmatites, lithium clays (hectorite), oilfield and geothermal brines, and lithium-bearing zeolites (Bradley and others, 2017). Pegmatites that comprise lithium ore belong to the lithium-cesium-tantalum (LCT) class of pegmatites, where the main ore mineral is spodumene, $LiAl(SiO_3)_2$.

Mineral Systems for Lithium Resources

Lithium is present in five different mineral systems (fig. 8). Table 10 lists examples of focus areas for different mineral systems and deposit types throughout the conterminous United States. Some basin brine path systems contain lithium that can be extracted from bromine or potash brines. Lacustrine evaporite systems occur in many western States where brines and lithium clays are preserved in playas. Spodumene-bearing LCT pegmatites represent potential lithium resources in porphyry Sn systems. Lithium occurs in some examples of Climax-type and magmatic REE systems, but those systems have not historically produced lithium.

Basin Brine Path

Basin brine systems include oilfield brines, such as the bromine brines in the areally extensive Smackover Formation lithium focus area in Arkansas, Texas, and Louisiana where lithium occurs as a byproduct. The Arkansas Smackover Formation lithium project includes two projects to extract lithium from bromine brines: (1) the Lanxess lithium project in south-central Arkansas where a demonstration lithium extraction plant was installed in 2019; the project was estimated to contain 3.14 Mt of lithium carbonate, and (2) extensive brine leases in the TETRA project in southwest Arkansas (Standard Lithium, 2020). The Paradox Basin focus area of Utah and Colorado includes occurrences of lithium in potash brines. For example, elevated concentrations of lithium and bromine were encountered during exploration of the Green River Potash Project (Gilbride and Santos, 2012).

Lacustrine Evaporite

Lacustrine evaporite systems form in closed drainage basins in arid environments where elements carried in surface waters, meteoric waters, or geothermal recharge waters are concentrated by evaporation. Lithium-bearing residual brines accumulate in aquifers below dry lake beds. Where lithium-rich brines encounter lake sediment, ash layers, or volcanic rocks, deposit of lithium clays and zeolites can form.

Most of the focus areas for lacustrine evaporite systems were defined on the basis of outlines of playas or one or more groups of HUC8 watersheds that encompass areas of known or potential lithium resources.

Porphyry Sn

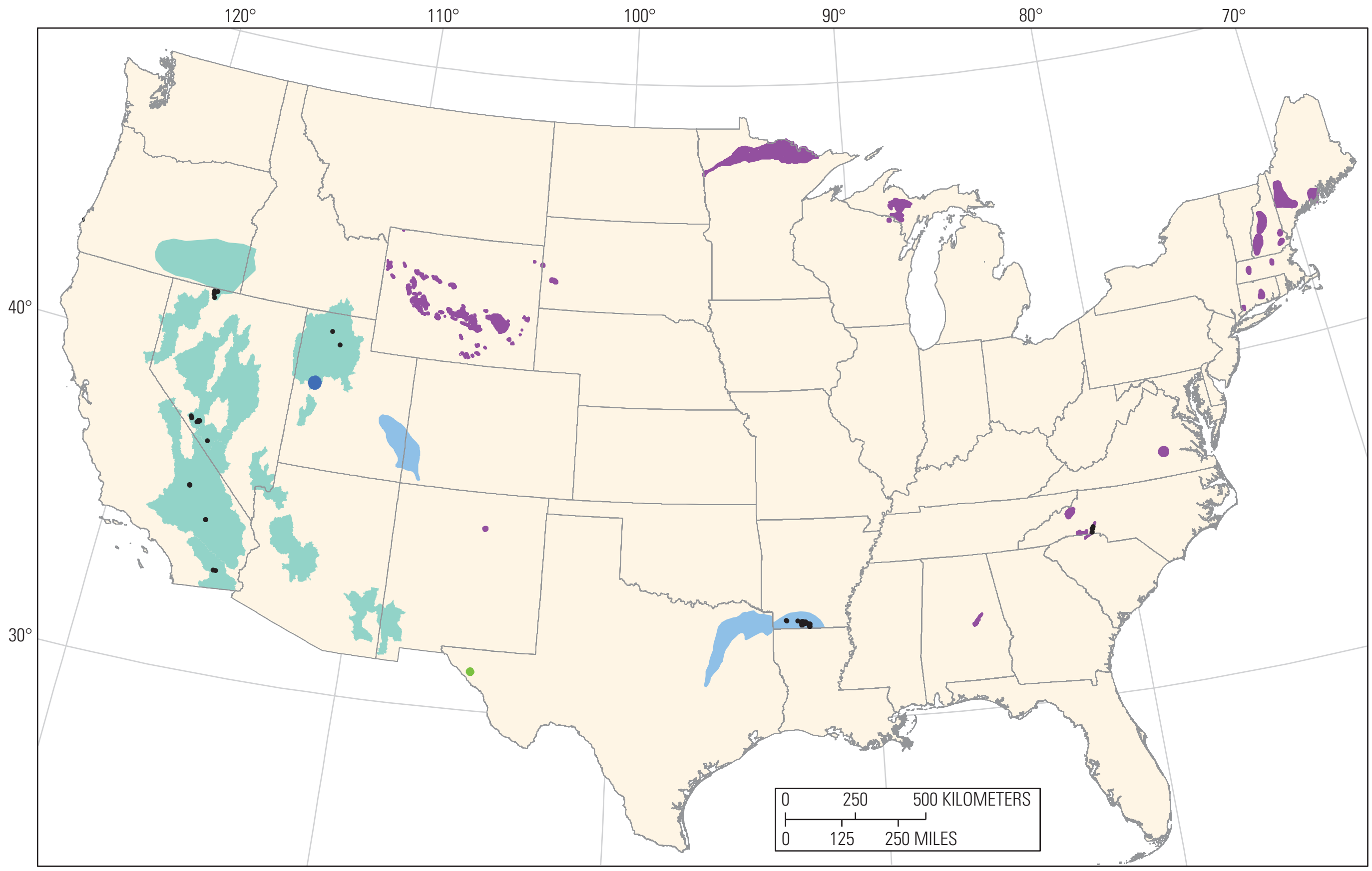
Granite-related porphyry Sn systems form in back arc or hinterland settings by similar processes from fluids exsolved from more crustally contaminated supracrustal (S-type) peraluminous plutons and stocks. At deep levels, LCT pegmatites emanate from plutons. Resulting ore deposits tend to be Cu and Mo poor and enriched in Li, cesium (Cs), Ta, Nb, Sn, tungsten (W), Ag, Sb, and In (Hofstra and Kreiner, 2020).

LCT pegmatites are found mainly in the eastern United States. Spodumene was mined in the Kings Mountain pegmatite district in North Carolina and South Carolina until 1998; production of downstream lithium products processed from spodumene concentrates continues in the area. For example, spodumene must be converted to battery-grade lithium hydroxide, lithium oxide, or lithium carbonate equivalent as a final product. Recent and ongoing exploration in the Carolina tin-spodumene belt has resulted in JORC-compliant (Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy, 2012) mineral resource estimates of 27.9 Mt of ore at an average grade of 1.11 percent lithium oxide (Li_2O) for the Core and Central properties near Charlotte, North Carolina (Piedmont Lithium Limited, 2019, 2020). Those ores consist of about 20 percent spodumene; the remaining quartz, feldspar, and mica represent byproduct industrial minerals.

A new spodumene pegmatite was recently discovered at Plumbago Mountain in western Maine (Oxford County Pegmatite Field focus area). The Plumbago North deposit is estimated to contain 10 Mt of ore with an average grade of 4.68 percent Li_2O, which makes it higher grade than top spodumene-producing mines globally (Simmons and others, 2020).

Other Systems

The Climax-type mineral system at the Spor Mountain volcanogenic beryllium deposit in Utah contains lithium, but lithium is not recovered. Texas Rare Earth Resources Corp. (2012) reported elevated concentrations of potentially recoverable lithium and beryllium at the Round Top REE project in Texas, an example of a magmatic REE system.



Political boundaries from Esri (2012).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 96° W, latitude of origin, 37.5°.
North American Datum of 1983.

Figure 8. Map showing focus areas and significant mineral occurrences for lithium resources in the conterminous United States. Mineral occurrences are sites that have a contained resource and (or) past production of lithium metal greater than 15,000 metric tons (Karl and others, 2019). REE, rare earth element; Sn, tin.

Table 10. Examples of mineral systems, deposit types, and focus areas for potential lithium resources in the conterminous United States.

[*, mineral systems and deposit types that are most likely to represent significant sources of lithium. See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types. Abbreviations: REE, rare earth element; Sn, tin; LCT, lithium-cesium-tantalum]

Mineral system	Deposit type	Focus area	State
Basin brine path	Basin brine	Smackover Formation lithium	Arkansas, Texas
		Paradox Basin lithium	Colorado, Utah
Climax-type	Volcanogenic beryllium Volcanogenic uranium Fluorspar	Spor Mountain/ Topaz Mountain	Utah
Lacustrine evaporite*	Lithium clay*	West central Arizona lithium	Arizona
	Residual brine*	Nevada lithium	Nevada
		Sevier Lake lithium	Utah
	Residual brine Lithium clay	McDermitt Caldera lithium	Nevada, Oregon
		Lordsburg Playa Lithium Project	New Mexico
Magmatic REE	Peralkaline syenite/granite/rhyolite/alaskite/ pegmatites	Round Top	Texas
Porphyry Sn (granite-related)*	Pegmatite (LCT)*	Black Hills Pegmatites	South Dakota, Wyoming
		Animikie Red Ace Pegmatite	Wisconsin
		Grafton pegmatite district	New Hampshire
		Oxford County Pegmatite Field	Maine
		Kings Mountain pegmatite district	North Carolina, South Carolina

Niobium and Tantalum

Importance to the Nation's Economy

Niobium and tantalum are considered together because they occur together in mineral deposits. Niobium is also known as columbium.

Niobium

The following two subsections describing factors indicating the importance of niobium to the Nation's economy are quoted from the "Mineral Commodity Summaries 2020" (U.S. Geological Survey, 2020, p. 114–115).

> *Domestic Production and Use:* Significant U.S. niobium mine production has not been reported since 1959. Companies in the United States produced niobium-containing materials from imported niobium concentrates, oxides, and ferroniobium. Niobium was consumed mostly in the form of ferroniobium by the steel industry and as niobium alloys and metal by the aerospace industry. In 2019, there was a decrease in reported consumption of niobium for high-strength low alloy steel and superalloy applications. Major end-use distribution of reported niobium consumption was as follows: steels, about 78%, and superalloys, about 22%. The estimated value of niobium consumption was $460 million, as measured by the value of imports.
>
> *World Resources:* World resources of niobium are more than adequate to supply projected needs. Most of the world's identified resources of niobium occur as pyrochlore in carbonatite (igneous rocks that contain more than 50%- by-volume carbonate minerals) deposits and are outside the United States. The

> United States has approximately 1,400,000 tons of niobium in identified resources, most of which were considered subeconomic at 2019 prices for niobium.

Tantalum

The following two subsections describing factors indicating the importance of tantalum to the Nation's economy are quoted from the "Mineral Commodity Summaries 2020" (U.S. Geological Survey, 2020, p. 164–165).

> *Domestic Production and Use:* Significant U.S. tantalum mine production has not been reported since 1959. Domestic tantalum resources are of low grade, some are mineralogically complex, and most are not commercially recoverable. Companies in the United States produced tantalum alloys, capacitors, carbides, compounds, and tantalum metal from imported tantalum ores and concentrates and tantalum-containing materials. Tantalum metal and alloys were recovered from foreign and domestic scrap. Domestic tantalum consumption was not reported by consumers. Major end uses for tantalum included alloys for gas turbines used in the aerospace and oil and gas industries; tantalum capacitors for automotive electronics, mobile phones, and personal computers; tantalum carbides for cutting and boring tools; and tantalum oxide (Ta_2O_5) was used in glass lenses to make lighter weight camera lenses that produce a brighter image. The value of tantalum consumed in 2019 was estimated to exceed $270 million as measured by the value of imports.

> *World Resources:* Identified world resources of tantalum, most of which are in Australia, Brazil, and Canada, are considered adequate to supply projected needs. The United States has about 55,000 tons of tantalum resources in identified deposits, most of which were considered uneconomic at 2019 prices for tantalum.

Mode of Occurrence

Niobium and tantalum have very similar physical and chemical properties and typically occur together in igneous intrusive rocks (Schulz, Piatak, and Papp, 2017). Niobium is dominant in carbonatites and associated alkaline rocks and peralkaline granites and pegmatites. Tantalum is dominant in lithium-cesium-tantalum (LCT) pegmatites. Physical weathering can form placer deposits containing concentrations of heavy minerals, including columbite, $Fe^{2+}Nb_2O_6$, and tantalite, $(Mn,Fe)(Ta,Nb)_2O_6$.

Mineral Systems for Niobium and Tantalum Resources

Niobium and tantalum occur in deposits that form in multiple mineral systems (fig. 9, table 11). Parent focus areas outline regional belts that are known to host examples of magmatic REE systems, which lie within the belts as child focus areas (fig. 9). Magmatic REE systems are the most likely hosts for significant deposits of niobium and tantalum. Chemical weathering of deposits associated with magmatic REE systems could form regolith (ion-adsorption) REE deposits, although none have been recognized.

Climax-Type

Climax-type systems occur in continental rifts with hydrous bimodal magmatism. Aqueous supercritical fluids exsolved from anorogenic (A-type) topaz rhyolite plutons and the apices of subvolcanic stocks form a variety of deposit types as they move upward and outward, split into liquid and vapor, react with country rocks, and mix with groundwater. The broad spectrum of deposit types results from the large thermal and chemical gradients in these systems. At deep levels in these systems, NYF (niobium-yttrium-fluorine) pegmatites emanate from plutons (Hofstra and Kreiner, 2020).

NYF pegmatites occur in several pegmatite districts in Colorado. The undeveloped Cave Peak porphyry molybdenum-niobium deposit in Texas is related to a mafic, alkaline intrusion (Audétat, 2010) and may be indicative of other deposits in the Trans-Pecos alkaline belt that extends into New Mexico.

Magmatic REE

The Elk Creek Project in Nebraska is being developed to mine the Elk Creek carbonatite. If developed, it will be the only niobium mine and primary niobium processing facility in the United States and will also produce scandium and titanium (U.S. Geological Survey, 2020). The Elk Creek carbonatite is a lower Paleozoic intrusive complex buried beneath 200 meters of sedimentary rocks. Niobium occurs as the mineral pyrochlore. A high-resolution airborne gravity gradient and magnetic survey flown over the carbonatite in 2012, combined with borehole and physical property data, provided an interpretation of the geophysical signature of the buried deposit and identified anomalies that could represent more mineralized rock at depth (Drenth, 2014). Niobium and tantalum also occur in a variety of peralkaline and related rocks, mainly in the western United States.

Placer

Placers and paleoplacers in Idaho and some other western States contain monazite, thorite, euxenite (yttrium, niobium, tantalum), and ilmenite (Staatz and others, 1979). Presumably the placers are residuum from weathering of the granitoid rocks of the Idaho batholith. In the 1950s, alluvial deposits in valleys in western Idaho were dredged and produced euxenite and columbite as well as ilmenite (Staatz and others, 1979). Table 11 lists some placer focus areas where niobium and tantalum minerals have been reported. Other placers throughout the country may contain these minerals, but few occurrences are well documented.

Porphyry Sn

Focus areas for LCT pegmatites that have reported niobium or tantalum are found mainly in the eastern States in pegmatites. These pegmatites also represent known and potential lithium resources because they are spodumene-bearing.

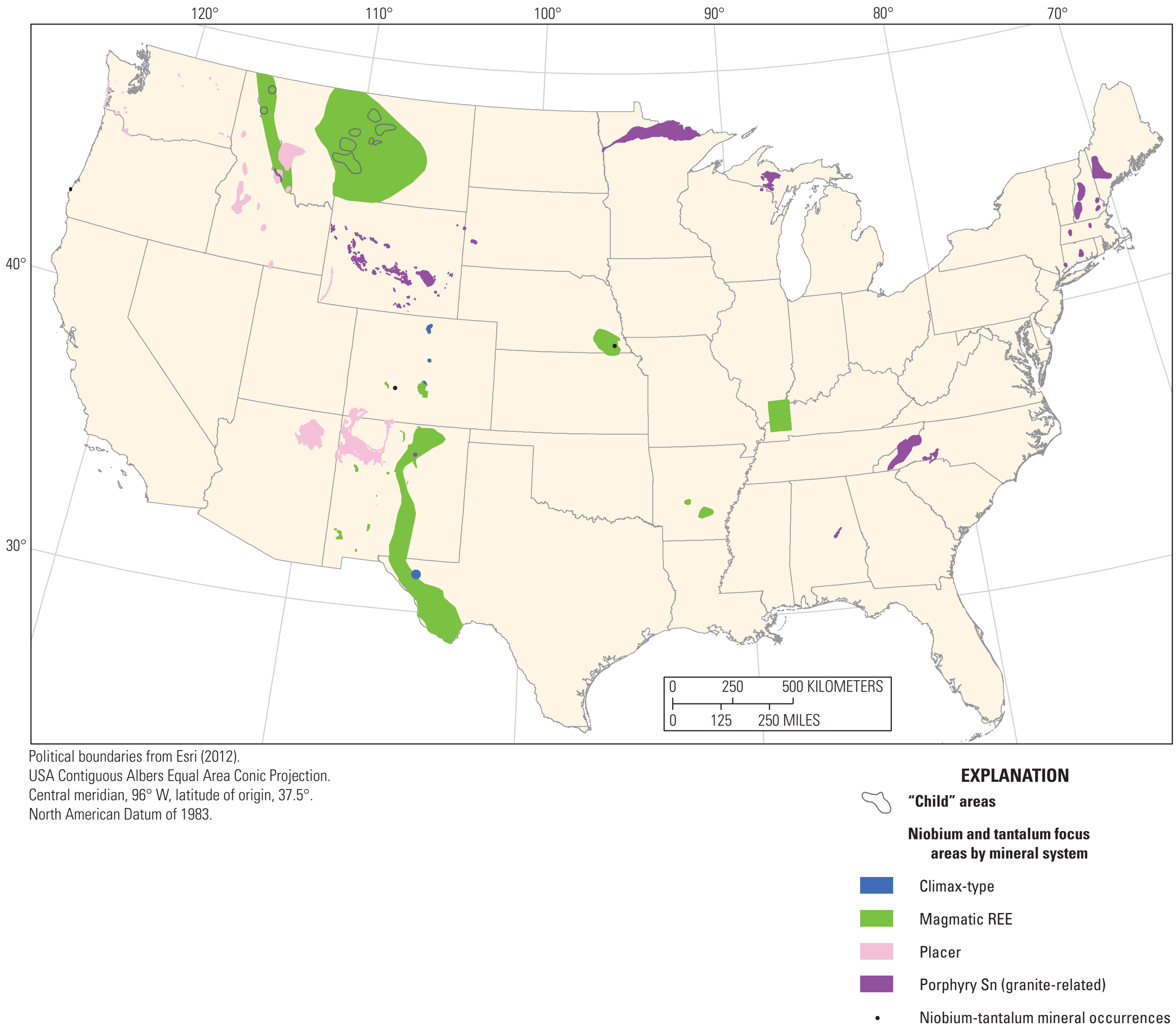


Figure 9. Map showing focus areas and selected mineral occurrences for niobium and tantalum resources in the conterminous United States. Mineral occurrences from Labay and others (2017). REE, rare earth element; Sn, tin.

Table 11. Examples of mineral systems, deposit types, and focus areas for potential niobium and tantalum resources in the conterminous United States.

[*, mineral systems and deposit types that are most likely to represent significant sources of niobium and tantalum. See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types. Abbreviations: NYF, niobium-yttrium-fluorine; Sn, tin; LCT, lithium-cesium-tantalum]

Mineral system	Deposit type	Focus area	State
Climax-type	Pegmatite (NYF)	Crystal Mountain pegmatites	Colorado
	Porphyry molybdenum	Cave Peak	Texas
Magmatic REE*	Carbonatite*	Elk Creek carbonatite	Nebraska
		Powderhorn District	Colorado
		Magnet Cove District- Potash Sulphur Springs	Arkansas
	Peralkaline syenite/granite/rhyolite/alaskite/pegmatites*	Platt Mine pegmatite	Wyoming
		Hicks Dome	Illinois
		Round Top	Texas
		Central Montana alkalic province	Montana, Wyoming
Placer	Columbite/tantalite	Idaho Columbite/Tantalite Placers	Idaho
	Monazite/xenotime	Spring Gap	Wyoming
Porphyry Sn (granite-related)	Pegmatite (LCT)	Southern Complex pegmatites	Michigan
		Black Hills Pegmatites	South Dakota, Wyoming
		Oxford County Pegmatite Field	Maine
		Spruce Pine pegmatite district	North Carolina
		Rociada	New Mexico

Platinum-Group Elements

Importance to the Nation's Economy

The following two subsections describing factors indicating the importance of platinum-group elements (or platinum-group metals) to the Nation's economy are quoted from the "Mineral Commodity Summaries 2020" (U.S. Geological Survey, 2020, p. 124–125).

> *Domestic Production and Use:* One company in Montana produced over 15,000 kilograms of platinum-group metals (PGMs) with an estimated value of about $680 million. Small quantities of primary PGMs also were recovered as byproducts of copper-nickel mining in Michigan; however, this material was sold to foreign companies for refining. The leading domestic use for PGMs was in catalytic converters to decrease harmful emissions from automobiles. Platinum-group metals are also used in catalysts for bulk-chemical production and petroleum refining; dental and medical devices; electronic applications, such as in computer hard disks, hybridized integrated circuits, and multilayer ceramic capacitors; glass manufacturing; investment; jewelry; and laboratory equipment.

> *World Resources:* World resources of PGMs are estimated to total more than 100 million kilograms. The largest reserves are in the Bushveld Complex in South Africa.

Mode of Occurrence

PGEs form in a variety of mineral systems and deposit types. Most of the world's PGEs come from magmatic deposits associated with large igneous provinces. PGEs also occur in hydrothermal and sedimentary deposits, in residual deposits and laterites in chemical weathering systems, and in placers (Zientek and others, 2017).

Mineral Systems for PGE Resources

Focus areas for PGEs in the conterminous United States are plotted by mineral systems on the map in figure 10. PGEs occur as a primary commodity in deposit types associated with mafic magmatic systems and as a byproduct in some porphyry deposits and placers. Table 12 lists examples of focus areas for different mineral systems and deposit types throughout the conterminous United States.

Mafic Magmatic

Magmatic PGE deposits are classified as conduit-type deposits, which occur as sills and dikes, or as reef- and contact-type deposits, which occur in layered mafic intrusions. The Eagle Mine of northern Michigan is an example of a conduit-type deposit (included in the Midcontinent Rift conduit-type magmatic sulfide Ni-Cu-PGE focus area). The J-M reef in the Stillwater Complex in Montana is an example a magmatic reef-type deposit. The Duluth Complex in Minnesota has potential for reef-type mineralization. PGEs also are found with Ni and Cu in disseminated Cu-Ni sulfide deposits.

Poorly documented potential PGE targets that would benefit from new data acquisition include the Dadeville Complex in Alabama, a reef-type deposit in Lake Owen’s Complex in Wyoming, and the Glen Mountains Complex in Oklahoma. Furthermore, new data could determine the extent of the J-M Reef at the Stillwater Complex in Montana.

Mafic rocks in Mesozoic rift basins of the eastern United States that are associated with the Central Atlantic magmatic province (CAMP) event represent speculative PGE resources with potential for large igneous province (LIP)-related conduit-style mineralization (Gottfried and Froelich, 1977). As part of a regional study of the distribution of strategic and critical minerals in tholeiitic rocks of the eastern United States, Gottfried and others (1990) reported anomalous concentrations of platinum, palladium, gold, and tellurium in diabase of the Gettysburg basin and proposed field relations and geochemical and petrographic guidelines for PGE exploration in the Mesozoic basins of the eastern United States. Ferrodiorite differentiates in these rocks may be enriched in PGEs similar to the geologic setting of the Skaergaard Complex in Greenland.

Placer

The only known productive PGE placer deposit in the United States is at Goodnews Bay in Alaska. Historical placer gold mines in northen California and along the Pacific coast in Oregon and Washington produced small amounts of PGEs in the early 1900s (Mertie, 1969; Peterson, 1994). In California, serpentine and ultramafic rocks in upstream drainage areas in the Klamath and Sierra Nevada Mountains represent the likely sources of PGEs. Many historical gold-PGE placer tailings are contaminated with mercury, which would require remediation as part of any reprocessing. However, transport and dispersal of tailings, land use changes over time, and low PGE grades of the placers suggest that these are unlikely to represent economically viable PGE resources (R. Ashley, U.S. Geological Survey, written commun., 2020). Further investigation would be needed to determine if historical tailings represent a potential source of PGE resources in the northwestern United States.

Porphyry Cu-Mo-Au

PGEs are reported as potential byproducts from some porphyry copper systems, especially in alkalic island arc porphyry copper deposits (John and Taylor, 2016). PGEs occur in telluride minerals and in solid solution in pyrite. Reported grades are less than 60 parts per billion platinum plus palladium. In the United States, PGEs are known to occur in the Allard porphyry copper deposit in Utah and in the Pebble deposit in Alaska (Tarkian and Stribrny, 1999; Gregory and others, 2013).

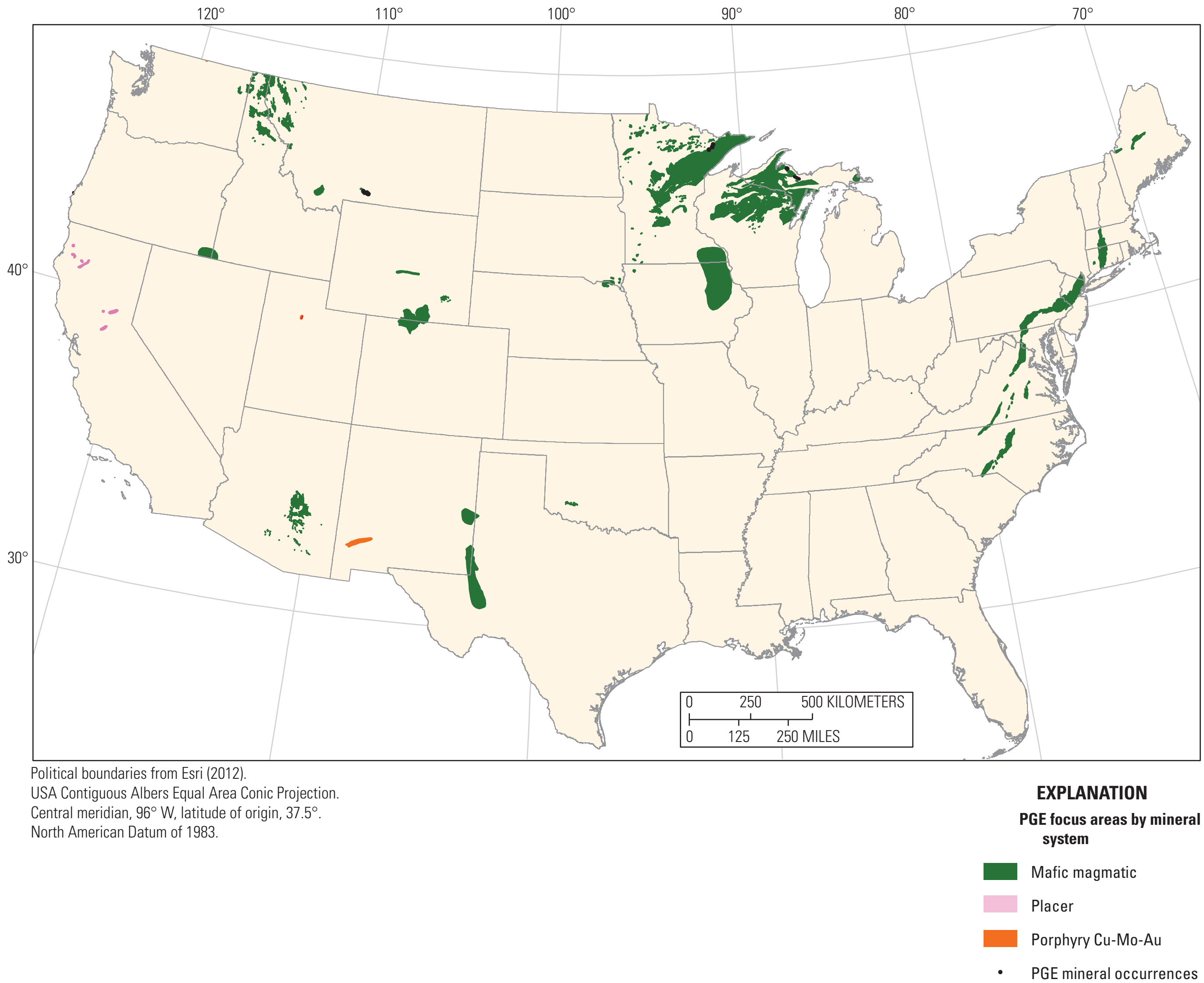


Figure 10. Map showing focus areas and selected mineral occurrences for platinum-group element (PGE) resources in the conterminous United States. Mineral occurrences from Labay and others (2017). Cu, copper; Mo, molybdenum; Au, gold.

Table 12. Examples of mineral systems, deposit types, and focus areas for potential platinum-group element (PGE) resources in the conterminous United States.

[*, mineral systems and deposit types that are most likely to represent significant sources of PGEs. See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types. Abbreviations: PGE, platinum-group element; Ni, nickel; Cu, copper; CAMP, Central Atlantic magmatic province; Mo, molybdenum; Au, gold]

Mineral system	Deposit type	Focus area	State
Mafic magmatic*	Nickel-copper-PGE sulfide*	Stillwater Complex	Montana
		Midcontinent Rift conduit-type magmatic sulfide Ni-Cu-PGE	Michigan, Minnesota, Wisconsin
		Otter Creek complex	Iowa
		CAMP event - Newark-Gettysburg Basin; Durham Basin	Maryland, Pennsylvania, New Jersey, New York; North Carolina
		Moxie Pluton	Maine
		Moyie	Idaho, Montana, Washington
		Wichita event - Glen Mountains Complex	Oklahoma
		Pecos	New Mexico, Texas
Placer	PGEs	Trinity County Placers	California
Porphyry Cu-Mo-Au	Porphyry/skarn copper	Tyrone-Chino-Hillsboro porphyry copper deposits	New Mexico
		Bingham	Utah

Rare Earth Elements

Importance to the Nation’s Economy

The following two subsections describing factors indicating the importance of rare earth elements to the Nation’s economy are quoted from the “Mineral Commodity Summaries 2020” (U.S. Geological Survey, 2020, p. 132–133).

> *Domestic Production and Use:* Rare earths were mined domestically in 2019. Bastnaesite (or bastnäsite), a rare-earth fluorocarbonate mineral, was mined as a primary product at a mine in Mountain Pass, CA, which was restarted in the first quarter of 2018 after being put on care-and-maintenance status in the fourth quarter of 2015. Monazite, a phosphate mineral, was produced as a separated concentrate or included as an accessory mineral in heavy-mineral concentrates. The estimated value of rare-earth compounds and metals imported by the United States in 2019 was $170 million, an increase from $160 million in 2018. The estimated distribution of rare earths by end use was as follows: catalysts, 75%; metallurgical applications and alloys, 5%; ceramics and glass, 5%; polishing, 5%; and other, 10%.
>
> *World Resources:* Rare earths are relatively abundant in the Earth’s crust, but minable concentrations are less common than for most other ores. In North America, measured and indicated resources of rare earths were estimated to include 2.7 million tons in the United States and more than 15 million tons in Canada.

Mode of Occurrence

The 15 lanthanide elements along with scandium and yttrium comprise the rare earth elements (REEs). Traditionally, the REEs are divided into two groups on the basis of atomic weight: (1) the light REEs (LREEs) are lanthanum through gadolinium (atomic numbers 57 through 64), and (2) the heavy REEs (HREEs) are terbium through lutetium (atomic numbers 65 through 71). Some authorities such as the International Union of Pure and Applied Chemistry include europium (atomic number 63) and gadolinium within the group of HREEs. Yttrium (Y), although light (atomic number 39), is included with the HREE group because of its similar chemical and physical properties and because it typically occurs in the same deposits as the lanthanides. Scandium (atomic number 21) is chemically similar to, and thus is sometimes included with, the REEs, but it does not commonly occur in economic concentrations in the same geological settings as the lanthanides and yttrium.

Geologic processes that can lead to formation of REE deposits include magmatism, magmatic-hydrothermal processes, metamorphism, surficial weathering, and sedimentary processes. The types of REE-bearing mineral deposits in the United States occur in a variety of mineral systems (Van Gosen and others, 2019). Within a given mineral system, a variety of different types of deposits can form. For example, magmatism can produce carbonatites, peralkaline igneous rocks, pegmatites, and REE-bearing veins. Recognizing one or more of these deposit types, igneous rocks with appropriate geochemistry, or distributions of such rocks in space and time could guide exploration for undiscovered domestic REE deposits. In addition to these bedrock and placer sources of REEs, coals and lignites represent potential sources of REEs. See Long and others (2010) for a description of the principal REE deposits of the United States.

Mineral Systems for REE Resources

Rare earth elements are the principal commodity in deposit types associated with magmatic REE systems. In other systems, REEs typically occur as byproducts or coproducts with other minerals. REEs can occur in a wide range of mineral systems and deposit types (fig. 11). Table 13 lists examples of focus areas for the main types of REE-bearing mineral systems. Phase 1 of Earth MRI identified focus areas for REEs (Hammarstrom and Dicken, 2019; Dicken and others, 2019). Those data are incorporated in phase 2. Note that the extent of REE mineralization in many of these areas remains to be determined, especially for the broad swaths of focus areas that represent areas of the United States that may or may not contain viable resources in phosphorites or clays.

Chemical Weathering

Regolith-hosted (aka in adsorption clay) REE deposits are an easily mined source of REEs that are currently mined only in China. The granite-derived regoliths contain lateritic clay deposits in which the REEs occur mainly as ions adsorbed to clay mineral surfaces. Mined deposits in China reportedly have grades in the range of 500 to over 3,000 ppm REEs (Bao and Zhao, 2008). Regolith-hosted REE deposits currently are the source of the world's supply of HREEs (gadolinium to lutetium). Ore-forming processes that result in HREE-enriched regolith deposits are poorly understood. Weathering environments that favor the release of the REEs in the shallow soils but preserve halloysite clays in deep regolith that can continuously adsorb REEs in the clay minerals may be instrumental in forming economically valuable HREE deposits (Li and Zhou, 2020). Similar deposits are currently under exploration in Brazil, the Philippines, and Madagascar (Smith and others, 2017). The Ambohimirahavavy deposit, Madagascar, hosts LREE-enriched ores that contain HREE concentrations similar to those of the South China ores, which suggests an economically viable REE source (Ram and others, 2019). Bulk rock total REE contents of the Madagascar deposits vary from 400 to 5,000 ppm, with HREEs varying from 10 to 20 percent of the total REEs (Smith and others, 2017). For some Madagascar deposits, metasomatism weathering by fluids derived from outside the granite system are thought to be influential in the enrichment of HREEs during lateritization (Smith and others, 2017). The Serra Verde, Brazil, REE deposit has a published inferred resource of more than 200 Mt at 1,600 ppm total REEs (Herrington and others, 2019). The profile at Serra Verde is characterized by a REE-depleted upper part with a zone of REE-accumulation in the lower, kaolinized section of the profile. Nb, Ta, gallium (Ga), and HREEs are enriched in the carapace and edges of the granite body.

The southeastern United States contains numerous anorogenic (A-type) and highly fractionated (I-type) granites, which constitute promising source rocks for REE-enriched regolith deposits owing to their inherent high concentrations of REE. Granites of the southeastern United States have undergone a long history of chemical weathering, resulting in thick granite-derived regoliths, akin to those of the South China REE regolith deposits. Recent studies (Foley and Ayuso, 2015; Bern and others, 2017) demonstrate that regolith resting on weathered granites of Virginia and South Carolina can attain grades comparable to those of deposits currently mined in China. For example, a regolith deposit developed on a Neoproterozoic A-type granite in Virginia has been shown to contain up to 2,880 ppm total REEs, with an average grade of 900 ppm total REEs. Cerium anomalies and REE patterns for the Virginia regolith are comparable to those of REE-enriched regolith deposits of China that contain neodymium, a high-value middle REE. The studies suggest a significant potential in the southeastern United States for regolith-hosted REE deposits of a type containing LREEs and yttrium, and an-as-yet unknown potential for HREE deposits.

Consequently, U.S. focus areas include highly weathered granitic rocks having a composition similar to the granites in China and containing comparable amounts of REEs (Foley and Ayuso, 2015). Focus areas outline broad, north-south trending belts of igneous rocks of Alleghanian, NeoAcadian, and Neoproterozoic age in the eastern United States and other areas in the central United States where these deposits could have formed.

Underclays (clay-rich strata underlying coal beds) throughout much of the eastern and central United States can be enriched in REEs. Thirteen focus areas outline regions of known underclays, fireclays, and paleosols associated with coal where geochemical analyses and characterization are needed to evaluate REE potential. Such clays are included in studies underway by the National Energy Technology Laboratory of the U.S. Department of Energy in the Rare Earth Elements from Coal and Coal Byproducts research and development program to develop methods for REE extraction as potential domestic REE resources (https://www.netl.doe.gov/sites/default/files/2019-04/2019-REE-Project-Portfolio.pdf).

IOA-IOCG

IOA and IOCG deposits are another source of domestic REEs, including possible concealed deposits in the Midcontinent region and exposed deposits in the eastern Adirondack highlands of northern New York, where new geophysical data would be especially beneficial. Historical mine waste associated with abandoned iron mines in the Adirondack Mountains represent another potential domestic REE source (Taylor and others, 2019). Mine production at the Pea Ridge IOCG deposit in Missouri stopped in 2001, leaving several hundred thousand metric tons of REE-bearing minerals, mainly apatite, in waste from processing of iron deposits (Grauch and others, 2010).

Magmatic REE

Carbonatites are the primary source of REEs on a global scale. The only active REE mine in the United States is the carbonatite deposit at Mountain Pass, California. Advanced exploration projects with REE resources in the United States include carbonatite deposits at Bear Lodge, Wyoming, and Elk Creek, Nebraska, as well as deposits in peralkaline igneous rocks at Bokan Mountain, Alaska, and Round Top, Texas (Van Gosen and others, 2017).

Placer

Monazite-xenotime-bearing placers were the major source of domestic REE production prior to the discovery of the Mountain Pass deposit in California in the 1960s. These types of placers form in fluvial deposits in streams and rivers and in coastal heavy-mineral sands. Many of the placers in the southeastern United States contain monazite, ilmenite, and zircon. Heavy-mineral sands are the principal global source of titanium oxide and zircon; monazite is not always recovered but is produced as a concentrate or included as an accessory mineral in heavy-mineral concentrates.

Other Systems

Marine chemocline systems throughout many areas of the United States host phosphorites that are enriched in REEs. Owing to the large aerial extent of the REE-bearing phosphorites, they represent significant estimated REE resources (Emsbo and others, 2015, 2016). Although no REEs are currently produced domestically from phosphate deposits, the technology to recover REEs is available and, unlike many other deposit types, they contain elevated concentrations of both LREEs and HREEs. LCT-type pegmatites associated with porphyry Sn systems, such as at Rociada, New Mexico, produced REEs (McLemore, 2014). Thorium-rich, REE-bearing laminae in gneiss at Music Valley, California, contain concentrations of monazite and xenotime. Thorium- and REE-bearing vein deposits at Lemhi Pass, on the Idaho-Montana border, represent an uncommon potential REE resource. REEs are reported in some mafic magmatic systems, such as in apatite in the Virginia nelsonite deposits, but these are unlikely to represent significant resources.

REEs in Climax-type, porphyry Cu-Mo-Au, and porphyry Sn systems have not been extensively characterized; monazite is a relatively abundant accessory mineral in alkaline plutons. Molybdenum ore at the Climax Mine, Colorado, contains 0.005 percent monazite (John and Taylor, 2016). Geochemical data on a suite of ores from selected deposits in the United States indicate total REE concentrations in the range 20 to 300 ppm (Centre for Exploration Targeting, 2018), or well below what would be considered economic cutoff grades. However, given the large volumes of tailings at active and inactive mine sites in the western United States, considerable resources of REEs or other critical minerals may be present.

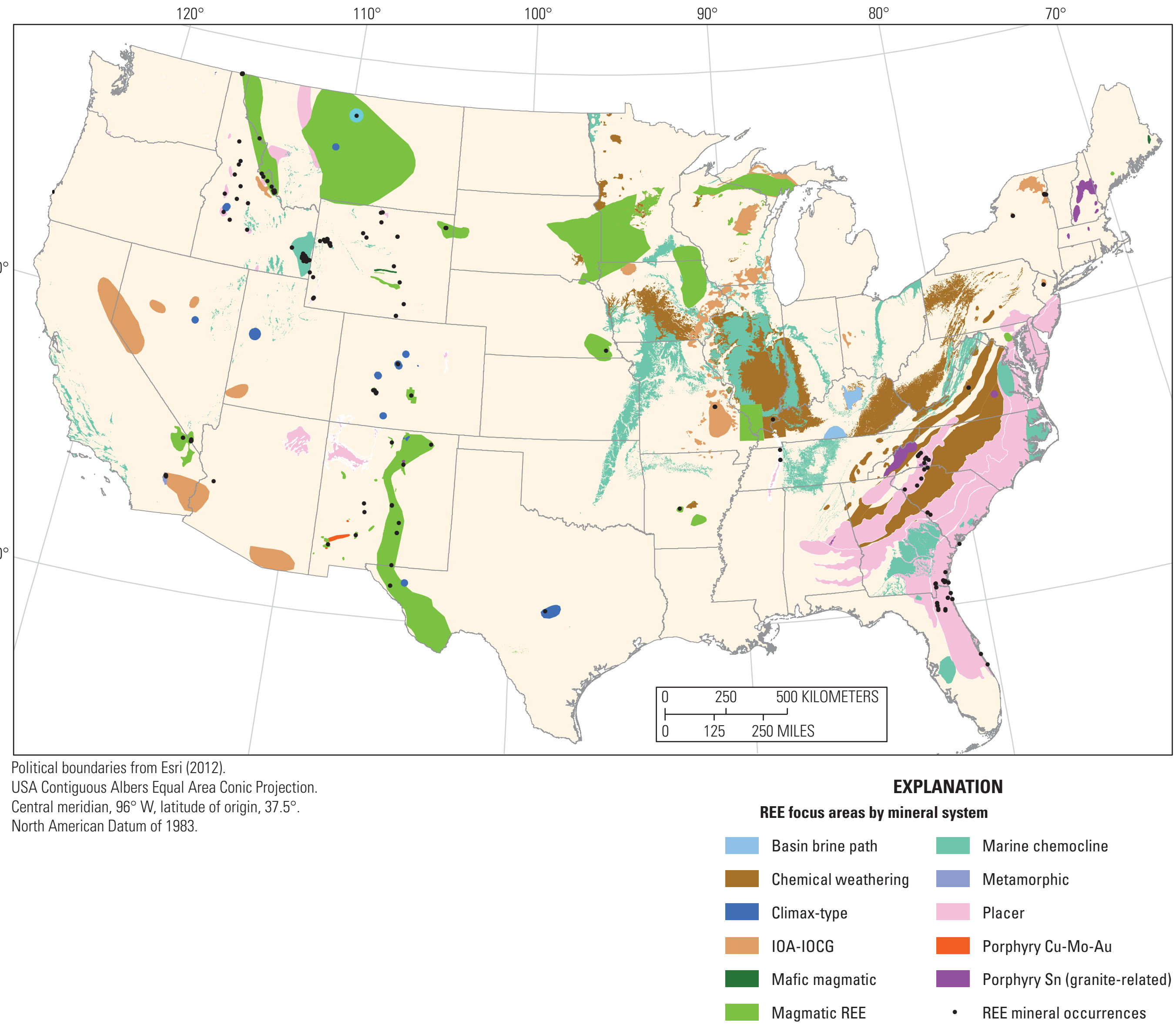


Figure 11. Map showing focus areas and significant mineral occurrences for rare earth element (REE) resources in the conterminous United States. Note that this map shows large regions of the country where examples of these mineral systems occur. Additional studies are needed to determine where any significant REE resources actually occur. Mineral occurrences include mined deposits, exploration prospects, and other occurrences with notable concentrations of REEs (Bellora and others, 2019). IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; Cu, copper; Mo, molybdenum; Au, gold; Sn, tin.

Table 13. Examples of mineral systems, deposit types, and focus areas for potential rare earth element (REE) resources in the conterminous United States.

[*, mineral systems and deposit types that are most likely to represent significant sources of REEs. See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types. Abbreviations: Fms, Formations; NYF, niobium-yttrium-fluorine; IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold]

Mineral system	Deposit type	Focus area	State
Chemical weathering	Regolith (ion adsorption) REEs	Alleghanian regolith	Alabama, Georgia, North Carolina, South Carolina, Virginia
	Clay	Pottsville and Allegheny Fms underclays	Maryland, Pennsylvania, West Virginia
Climax-type	Pegmatite (NYF)	South Platte pegmatites	Colorado
	Porphyry molybdenum	Cave Peak	Texas
IOA-IOCG	Iron oxide-apatite	Adirondack magnetite-apatite deposits	New York, Vermont
Magmatic REE*	Carbonatite*	Mountain Pass	California, Nevada
	Peralkaline syenite/granite/rhyolite/alaskite/pegmatites*	Wet Mountains	Colorado
		Hicks Dome	Illinois
Marine chemocline*	Phosphate*	Upper Ordovician Phosphate	Illinois, Iowa, Minnesota, Missouri
Metamorphic	Gneiss REEs	Music Valley	California
Placer*	Monazite/xenotime*	Fall Zone Placers	Alabama, Delaware, District of Columbia, Georgia, Maryland, New Jersey, North Carolina, Pennsylvania, South Carolina, Virginia
		Middle Shoreline Placers	Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia
		Idaho REE placers and paleo-placers	Idaho

Tin

Importance to the Nation's Economy

The following two subsections describing factors indicating the importance of tin to the Nation's economy are quoted from the "Mineral Commodity Summaries 2020" (U.S. Geological Survey, 2020, p. 172–173).

> *Domestic Production and Use:* Tin has not been mined or smelted in the United States since 1993 and 1989, respectively. Twenty-five firms accounted for over 90% of the primary tin consumed domestically in 2019. The major uses for tin in the United States were tinplate, 21%; chemicals, 17%; solder, 14%; alloys, 10%; babbitt, brass and bronze, and tinning, 11%; and other, 27%. Based on the average Platts Metals Week New York dealer price for tin, the estimated value of imported refined tin in 2019 was $703 million, and the estimated value of tin recovered from old scrap domestically in 2019 was $213 million.

> *World Resources:* Identified resources of tin in the United States, primarily in Alaska, were insignificant compared with those of the rest of the world. World resources, principally in western Africa, southeastern Asia, Australia, Bolivia, Brazil, Indonesia, and Russia, are extensive and, if developed, could sustain recent annual production rates well into the future.

Mode of Occurrence

The primary sources of global tin are placer deposits and granite-related tin deposits (Kamilli and others, 2017). The most prospective areas for domestic sources of tin are in Alaska. Descriptions of mineral regions, mines, and mineral deposits within the United States that are reported to contain enrichments of tin (Sn) are included in a data release of sites with publicly available records of past production of tin, or a defined resource of tin, or both (Karl and others, 2018). More than one-half of the sites are in Alaska.

Mineral Systems for Tin Resources

Granite-related tin deposits occur in Climax-type, porphyry Sn, and less commonly, porphyry Cu-Mo-Au systems (table 14, fig. 12). Although tin is reported at a few localities in other systems, these are not likely to represent significant resources.

Climax-Type

Climax-type systems in Nevada, Texas, and New Mexico contain tin. The Taylor Creek focus area in New Mexico, for example, outlines a Climax-type system and associated cassiterite placers. Greisen at McCullough Butte in Nevada contains tin and tungsten, but these are not considered to be viable products (Peter Vikre, U.S. Geological Survey, written commun., 2020). The Izenhood focus area in the Trinity Range, Nevada, was mined on a small scale in the 1930s and 1950s with no reported production; the narrow veinlets are considered too narrow for economic extraction (Bentz and Tingley, 1983, p. 119–120). Tailings at the Climax porphyry molybdenum mine in Colorado were processed to recover cassiterite and wolframite until 1982 (Kamilli and others, 2017).

Porphyry Sn

Porphyry Sn systems mainly occur in Alaska. In the conterminous United States, examples of these systems include the Alabama tin belt, the Irish Creek district in Virginia, and the Silver Hill Mine in Washington, all of which produced small amounts of tin in the early 1900s. The Alabama tin belt includes the McAllister Sn-Ta deposit, a complex, cassiterite-bearing pegmatite that included ‘greisen-like’ pipes hosted by the Rockford Granite, an approximately 300-Ma two-mica, peraluminous tin-bearing granite (Foord and Cook, 1989). The Coosa cassiterite mine, Alabama, operated in the early 1940s to produce cassiterite concentrate (Hunter, 1944).

LCT-type pegmatites in porphyry Sn systems carry tin with or without tungsten. Examples include the pegmatites in the Black Hills Pegmatites focus area of South Dakota and Wyoming. A few metric tons of tin were produced from tin skarn deposits in the Gorman district of southern California in the 1940s (Wiese and Page, 1946).

Other Systems

Tin is present in some examples of other mineral systems such as porphyry Cu-Mo-Au as a potential byproduct along with many other minor commodities. In these systems, tin would most likely be present in economic concentrations in mine waste rather than in primary ore. Cassiterite placers are associated with rhyolite-hosted tin in the Taylor Creek focus area, New Mexico. Historically, cassiterite was recovered at some gold placers in the western United States.

Table 14. Examples of mineral systems, deposit types, and focus areas for potential tin resources in the conterminous United States.

[*, mineral systems and deposit types that are most likely to represent significant sources of tin. See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types. Abbreviations: IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; PGE, platinum-group element; REE, rare earth element; Cu, copper; Mo, molybdenum; Au, gold; S-R-V-IS, skarn, replacement, vein, or intermediate sulfidation epithermal; Sn, tin; LCT, lithium-cesium-tantalum]

Mineral system	Deposit type	Focus area	State
Climax-type*	Greisen*	McCullough Butte	Nevada
	Porphyry molybdenum*	Cave Peak	Texas
		Climax-Sweet Home	Colorado
	Rhyolite tin	Izenhood (Trinity Range)	Nevada
IOA-IOCG	Iron oxide-copper-gold	Western Upper Peninsula IOCG	Michigan, Wisconsin
Magmatic REE	Peralkaline syenite, granite, rhyolite, alaskite, pegmatites	Adel Mountain Volcanics	Montana
Placer	Cassiterite	Gravel Range Mining District	Idaho
		Middle Tertiary Taylor Creek Rhyolite tin and placers	New Mexico
Porphyry Cu-Mo-Au	Lithocap alunite	Paradise Peak	Nevada
	Polymetallic sulfide S-R-V-IS	Marysville	Montana
	Porphyry/skarn copper	Bingham	Utah
Porphyry Sn*	Greisen*	Tin in Eastern Maine	Maine
		Irish Creek tin	Virginia
	Pegmatite (LCT)	Black Hills Pegmatites	South Dakota, Wyoming

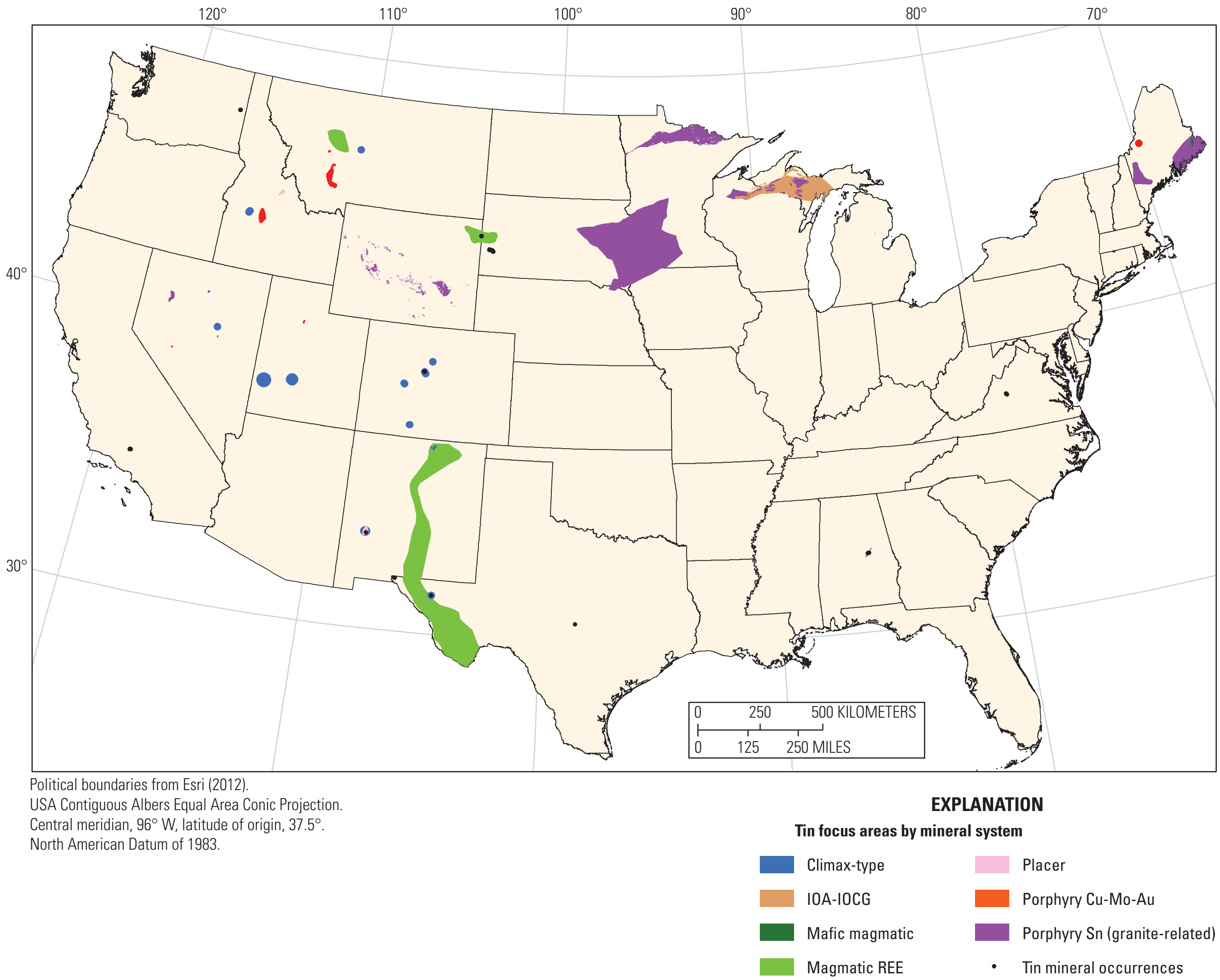


Figure 12. Map showing focus areas and significant mineral occurrences for tin resources in the conterminous United States. Mineral occurrences are sites with publicly available records of past production of tin, or a defined resource of tin, or both (Karl and others, 2018). IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; REE, rare earth element; Cu, copper; Mo, molybdenum; Au, gold.

Titanium

Importance to the Nation's Economy

The following two subsections describing factors indicating the importance of titanium to the Nation's economy are quoted from the "Mineral Commodity Summaries 2020" (U.S. Geological Survey, 2020, p. 176–177).

> *Domestic Production and Use:* At the beginning of 2019, two companies were recovering ilmenite and rutile concentrates from surface-mining operations near Nahunta, GA, and Starke, FL. In August, the owner of the operation in Florida acquired the operations in Georgia. A third (separate) company processed existing mineral sands tailings in Florida. Based on reported data through October 2019, the estimated value of titanium mineral and synthetic concentrates imported into the United States in 2019 was $840 million. Zircon was a coproduct of mining from ilmenite and rutile deposits. About 90% of titanium mineral concentrates were consumed by domestic titanium dioxide (TiO_2) pigment producers. The remaining 10% was used in welding-rod coatings and for manufacturing carbides, chemicals, and titanium metal.
>
> *World Resources:* Ilmenite accounts for about 89% of the world's consumption of titanium minerals. World resources of anatase, ilmenite, and rutile total more than 2 billion tons.

Mode of Occurrence

The mineral ilmenite, $FeTiO_3$, is the major global source of titanium. Other titanium minerals that are mined include hemo-ilmenite, titanomagnetite, rutile, perovskite, brookite, anatase, and leucoxene (Woodruff and others, 2017). Titanium minerals are mainly produced from fluvial sands, coastal heavy-mineral sands, or placer and paleoplacer deposits.

Mineral Systems for Titanium Resources

Titanium is a primary commodity in placer and mafic magmatic mineral systems (fig. 13, table 15). Unconventional titanium resources may be present in other systems as byproducts.

Mafic Magmatic

Iron-titanium oxide deposits associated with anorthosites are an important source of titanium globally from hard rock sources. The Roseland anorthosite in Virginia, for example, contains more than 1 Mt of ilmenite and abundant rutile. The nelsonite dikes associated with the complex are composed of ilmenite and apatite.

Placer

Nineteen focus areas for ilmenite-rutile-leucoxene placer deposits were delineated throughout the country. The most historically productive titanium placer deposits are along the coastal areas of the southeastern United States; many deposits also contain zircons and REEs in monazite and xenotime. Extensive focus areas for placers in the southeastern United States were defined on the basis of favorable geology (Fall Zone, shoreline boundaries); known producers, prospects, and occurrences; geophysical anomalies (radiometric thorium); and geochemical data (Ti, REEs, Y). Placer focus areas in the west include fluvial placers and paleoplacers developed along Cretaceous shorelines, such as the Fox Hills sandstone focus areas in Colorado and placers in Idaho. The paleoenvironments of the Fox Hills paleoplacers and some other areas associated with the Cretaceous seaway of the western interior of the United States are analogous to the depositional environment of some of the productive Cenozoic ilmenite placers of Georgia and Florida (Pirkle and others, 2012).

Other Systems

Other potential titanium sources include hydrothermal rutile, TiO_2, in porphyry Cu-Au-Mo deposits such as Bingham, Utah, with reported resources of 4,000,000 t of contained TiO_2 resources in the form of rutile and its polymorphs (Force and Creely, 2000). Iron oxide-apatite deposits in the Adirondack Mountains of New York such as the Port Leyden deposit produced ilmenite. Chemical weathering systems can be enriched in titanium. Aluminum-rich underclays associated with Pennsylvanian coal fields in the eastern United States may contain titanium as well as aluminum and REE resources. Bauxites developed on basaltic rocks are enriched in titanium as well as aluminum. Bauxite areas in the Pacific Northwest and Hawaii would have been considered potential resources had the bauxites been mined. However, residential land use in those areas and mineral economics render those resources unavailable (Force and Creely, 2000).

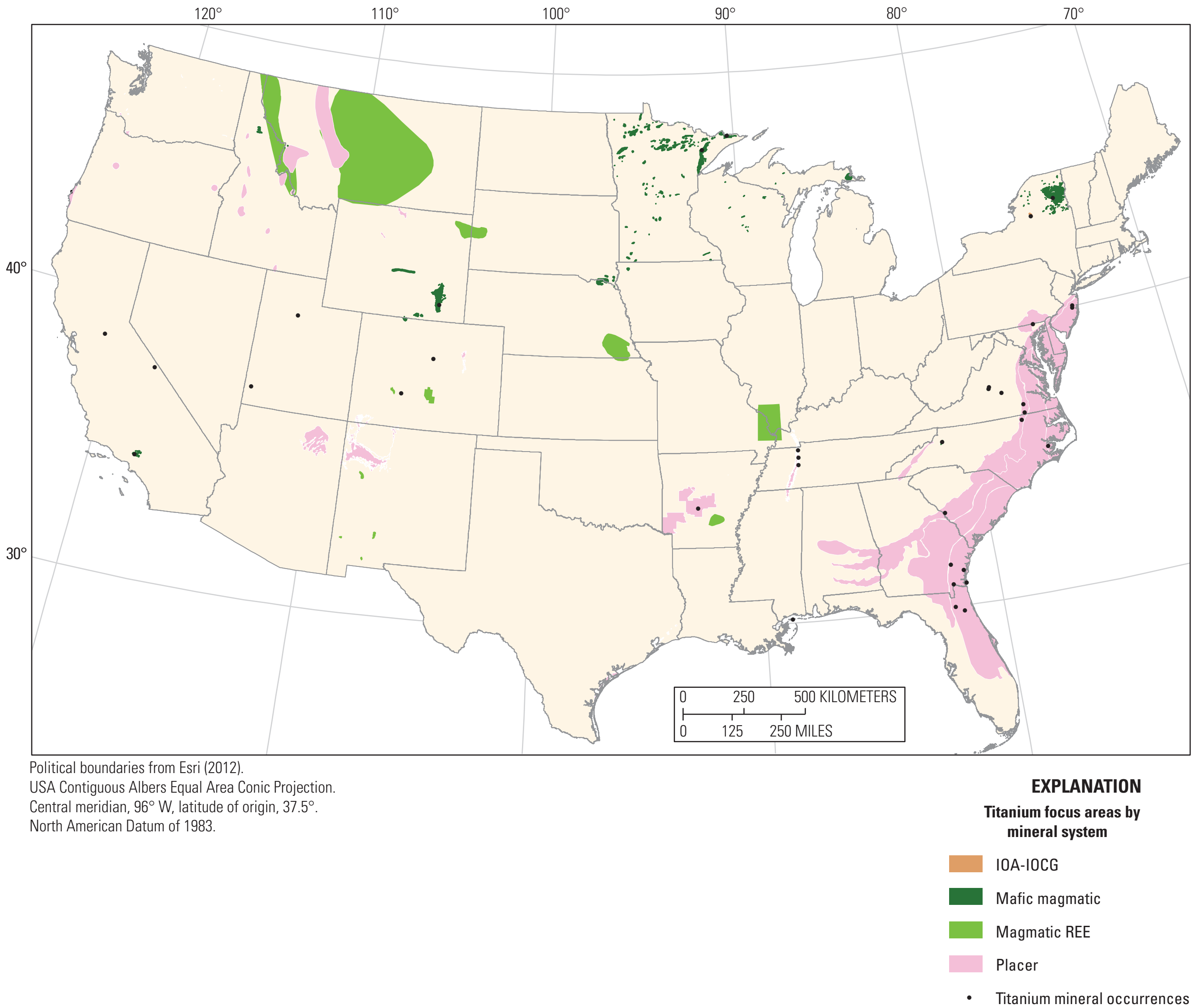


Figure 13. Map showing focus areas and significant mineral occurrences for titanium resources in the conterminous United States. Mineral occurrences from Labay and others (2017). IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; REE, rare earth element.

Table 15. Examples of mineral systems, deposit types, and focus areas for potential titanium resources in the conterminous United States and Hawaii.

[*, mineral systems and deposit types that are most likely to represent significant sources of titanium. See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types. Abbreviations: IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; REE, rare earth element]

Mineral system	Deposit type	Focus area	State
IOA-IOCG	Iron oxide-apatite	Port Leyden	New York
Mafic magmatic*	Iron-titanium oxide*	Laramie Anorthosite Complex	Wyoming
		Roseland mineral district	Virginia
		Yadkin-Richland district	North Carolina
Magmatic REE	Carbonatite	Elk Creek carbonatite	Nebraska
		Magnet Cove District- Potash Sulphur Springs	Arkansas
	Peralkaline syenite/granite/rhyolite/alaskite/pegmatites	Smokey Butte	Montana
		Hicks Dome	Illinois
Placer*	Ilmenite/rutile/leucoxene*	Fox Hills sandstone heavy-mineral placers	Colorado
		Middle Shoreline Placers	Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia

Tungsten

Importance to the Nation's Economy

The following two subsections describing factors indicating the importance of tungsten to the Nation's economy are quoted from the "Mineral Commodity Summaries 2020" (U.S. Geological Survey, 2020, p. 178–179).

> *Domestic Production and Use:* There has been no known domestic commercial production of tungsten concentrates since 2015. Approximately six companies in the United States used chemical processes to convert tungsten concentrates, ammonium paratungstate (APT), tungsten oxide, and (or) scrap to tungsten metal powder, tungsten carbide powder, and (or) tungsten chemicals. Nearly 60% of the tungsten used in the United States was used in cemented carbide parts for cutting and wear-resistant applications, primarily in the construction, metalworking, mining, and oil and gas drilling industries. The remaining tungsten was used to make various alloys and specialty steels; electrodes, filaments, wires, and other components for electrical, electronic, heating, lighting, and welding applications; and chemicals for various applications. The estimated value of apparent consumption in 2019 was approximately $700 million.

> *World Resources:* World tungsten resources are geographically widespread. China ranks first in the world in terms of tungsten resources and reserves and has some of the largest deposits. Canada, Kazakhstan, Russia, and the United States also have significant tungsten resources.

Mode of Occurrence

The minerals scheelite, $CaWO_4$, and wolframite, $(Fe,Mn)WO_4$, are the principal tungsten ore minerals. Tungsten skarns, the deposit type from which most the world's tungsten is produced, form in contact zones between I-type, intermediate composition intrusive rocks and limestones or other carbonate-bearing rocks. These minerals also occur in vein and breccia deposits; as coproducts and byproducts with molybdenum, tin, and silver in porphyry-type deposits; in greisens; and in pegmatites (British Geological Survey, 2011). Wolframite veins occur in non-carbonate rocks in some porphyry systems. Tungsten also occurs in hot springs systems and brines. Tungsten is concentrated with other heavy minerals in placers. Tungsten-bearing placer deposits and anomalous tungsten in stream sediments are exploration guides for lode deposits.

Mineral Systems for Tungsten Resources

Ninety-two focus areas are identified for potential tungsten resources in 10 different mineral systems (fig. 14, table 16). Mineral systems that comprise deposit types related to intrusive igneous rocks are the most likely sources of domestic tungsten resources.

Alkalic Porphyry

Tungsten occurs in alkalic porphyry systems associated with the Cretaceous Cuttingsville stock in Vermont and in veins and skarns in two gold-tungsten-tellurium mining districts in southeastern New Mexico (fig. 14). None of these have produced tungsten. The New Mexico occurrences warrant further study to determine the nature of the systems.

Lacustrine Evaporite

Searles Lake, a dry lake and brine in southern California, is a significant domestic tungsten resource that has never been exploited for tungsten, although the lake is a major domestic producer of borate. The lake is estimated to contain 170 million pounds of tungsten trioxide (WO_3) (Carpenter and Garrett, 1959). A demonstration project by the U.S. Bureau of Mines was successful in extracting tungsten from the brine using a novel ion exchange resin (Altringer and others, 1981).

Orogenic

Tungsten was produced during World War II from complex gold-antimony-tungsten deposits in the Yellow Pine district, Idaho. The focus area includes Midas Gold's Stibnite Gold restoration and development project to produce gold, antimony, and silver, but not tungsten (Zinnser, 2020).

Placer

Wolframite/scheelite placers are associated with tungsten skarn districts in eastern California. The Atolia mining district in California produced tungsten from both veins and placers mainly in the early 1900s, but intermittently up until 1940 (Lemmon and Dorr, 1940). Some of the Atolia placers primarily produced tungsten and the associated gold was not recovered. As in other areas of the West, tungsten exploration and development was active in wartime because tungsten was considered a strategic mineral.

Porphyry Cu-Mo-Au and Porphyry Sn

More than one-half of the tungsten focus areas represent skarn, replacement, or vein deposit types (S-R-V tungsten) in porphyry Cu-Mo-W systems. Tungsten skarns were extensively mined in the Pine Creek area of California, in the Great Basin of Nevada and Utah, and in southwestern Montana and Idaho. These areas contain significant unmined resources. The Springer Mine in the Mill City district focus area in Nevada was put on care-and-maintenance status in the 1980s owing to low tungsten prices. Focus areas in Nevada include deposits and resources at the Springer, Pilot Mountain, and Indian Springs Mines that have been drilled and evaluated since 2000 (for example, Thor Mining, 2020). The Calvert skarn in Montana produced tungsten in the 1950s and was re-examined in the mid-1960s and circa 2013 with geophysical surveys and drilling. There has been little to no production from these deposits and resources for decades. In addition to scheelite-bearing tungsten skarns associated with porphyry Cu-Mo-Au systems in the western United States, wolframite veins are also common.

Tungsten was produced along with tin and beryllium in the 1880s from greisen associated with the porphyry Sn system at the Irish Creek mine in Virginia. Tungsten occurs with tin at the Silver Hill porphyry tin deposit in Washington.

Other Systems

The only example of an arsenide system identified in this study is the tungsten-bearing five-element vein deposit in the Black Hawk Mining District focus area in New Mexico. Tungsten occurs in some deposits associated with alkaline igneous rocks in the magmatic REE systems in the Central Montana alkalic province and the Texas-New Mexico alkaline belt, typically in association with gold. Hot springs, such as Golconda in Nevada also represent potential domestic tungsten resources. Tungsten is reported as a trace commodity present in some nickel-copper-cobalt occurrences (mafic magmatic systems) but none of these types of deposits have produced tungsten.

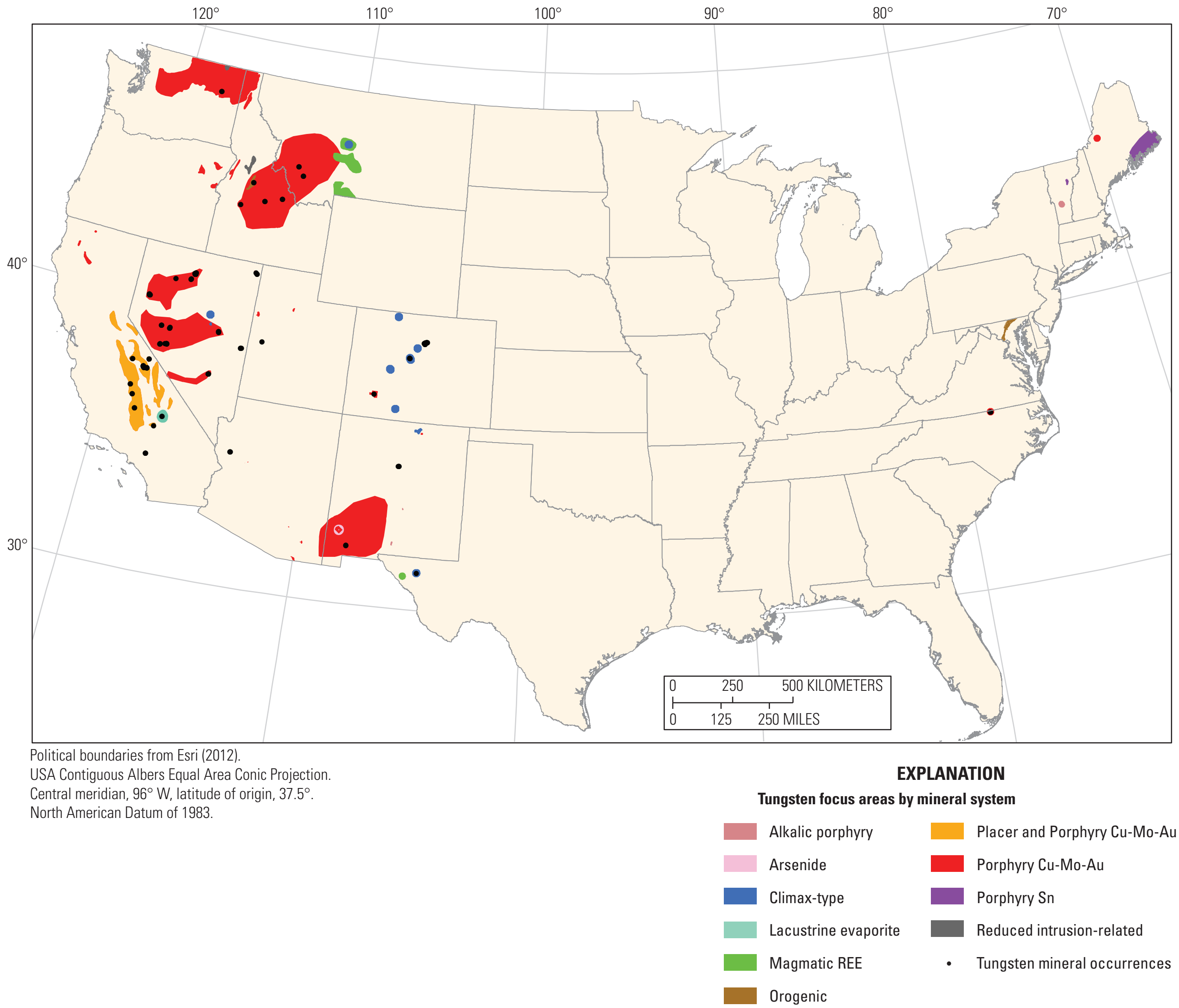


Figure 14. Map showing focus areas and significant mineral occurrences for tungsten resources in the conterminous United States. Mineral occurrences from Labay and others (2017). REE, rare earth element; Cu, copper; Mo, molybdenum; Au, gold; Sn, tin.

Table 16. Examples of mineral systems, deposit types, and focus areas for potential tungsten resources in the conterminous United States.

[*, mineral systems and deposit types that are most likely to represent significant sources of tungsten. See Hofstra and Kreiner (2020) for detailed descriptions of mineral systems and deposit types. Abbreviations: S-R-V-IS, skarn, replacement, vein; or intermediate sulfidation epithermal; PGE, platinum-group element; REE, rare earth element; Cu, copper; Mo, molybdenum; Au, gold; Sn, tin]

Mineral system	Deposit type	Focus area	State
Alkalic porphyry	Porphyry/skarn copper-gold	Cuttingsville stock	Vermont
Arsenide	Five-element veins	Black Hawk Mining District	New Mexico
Climax-type	Greisen Fluorspar	McCullough Butte	Nevada
	Porphyry molybdenum	Questa-Log Cabin-Spring Gulch	New Mexico
	Porphyry molybdenum Polymetallic sulfide S-R-V-IS Greisen	Climax-Sweet Home	Colorado
Lacustrine evaporite	Residual brine	Searles Lake	California
Magmatic REE	Peralkaline syenite/granite/rhyolite/alaskite/pegmatites	Round Top	Texas
Orogenic	Gold	Yellow Pine Mining District	Idaho
Placer	Wolframite/scheelite	Eastern California tungsten	California, Nevada
		Atolia Mining District	California
Porphyry Cu-Mo-Au*	S-R-V tungsten*	Rock Creek-Lost Creek Mining Districts	Montana
		Mount Tolman	Washington
		Tungsten Queen (Hamme) deposit	North Carolina, Virginia
		Tierra Blanca Mining District	New Mexico
		Mill City District	Nevada
		Gold Hill Mining District	Utah
Porphyry Sn (granite-related)	Greisen	Irish Creek tin	Virginia
	Porphyry/skarn	Knox Mountain pluton	Vermont

Discussion

Interest in materials needed for new technologies underscores the need for new data to identify domestic resources in critical minerals. Lithium, cobalt, and REEs are among the critical minerals in demand for established and emerging applications. Some of the factors that can affect availability of critical mineral commodities include concentration of production in a few countries, trade tensions, political instability, labor issues, declining ore grades, and economics of commodities produced primarily as byproducts. A recent evaluation of mineral commodity supply risk of the U.S. manufacturing sector identified cobalt, niobium, REEs, and tungsten as the critical commodities that pose the greatest supply risk (Nassar and others, 2020).

The phase 1 report on REEs (Hammarstrom and Dicken, 2019) identified deposits associated with carbonatites and peralkaline rocks, iron oxide-apatite deposits, and monazite-bearing placers as the most likely potential sources for newly developed domestic REE deposits. Acquisition of new data for some of these systems was begun in phase 1 (see fig. 1). Phosphorites (phosphate rock) currently mined in the United States could produce a significant amount of REEs as a byproduct (Emsbo and others, 2015, 2016). A high-resolution aeromagnetic and airborne radiometric survey is being conducted in areas of REE-rich phosphate horizons in northern Arkansas to map the aerial distribution of this important domestic source of HREEs and provide a pilot study for geophysical mapping of other REE-enriched phosphate units in the United States. Evaluation of the resource potential of phosphorites and regolith-hosted deposits, as well as the potential for REEs and aluminum in underclays, requires identification of priority study areas for geological mapping accompanied by geochemical analysis of candidate materials.

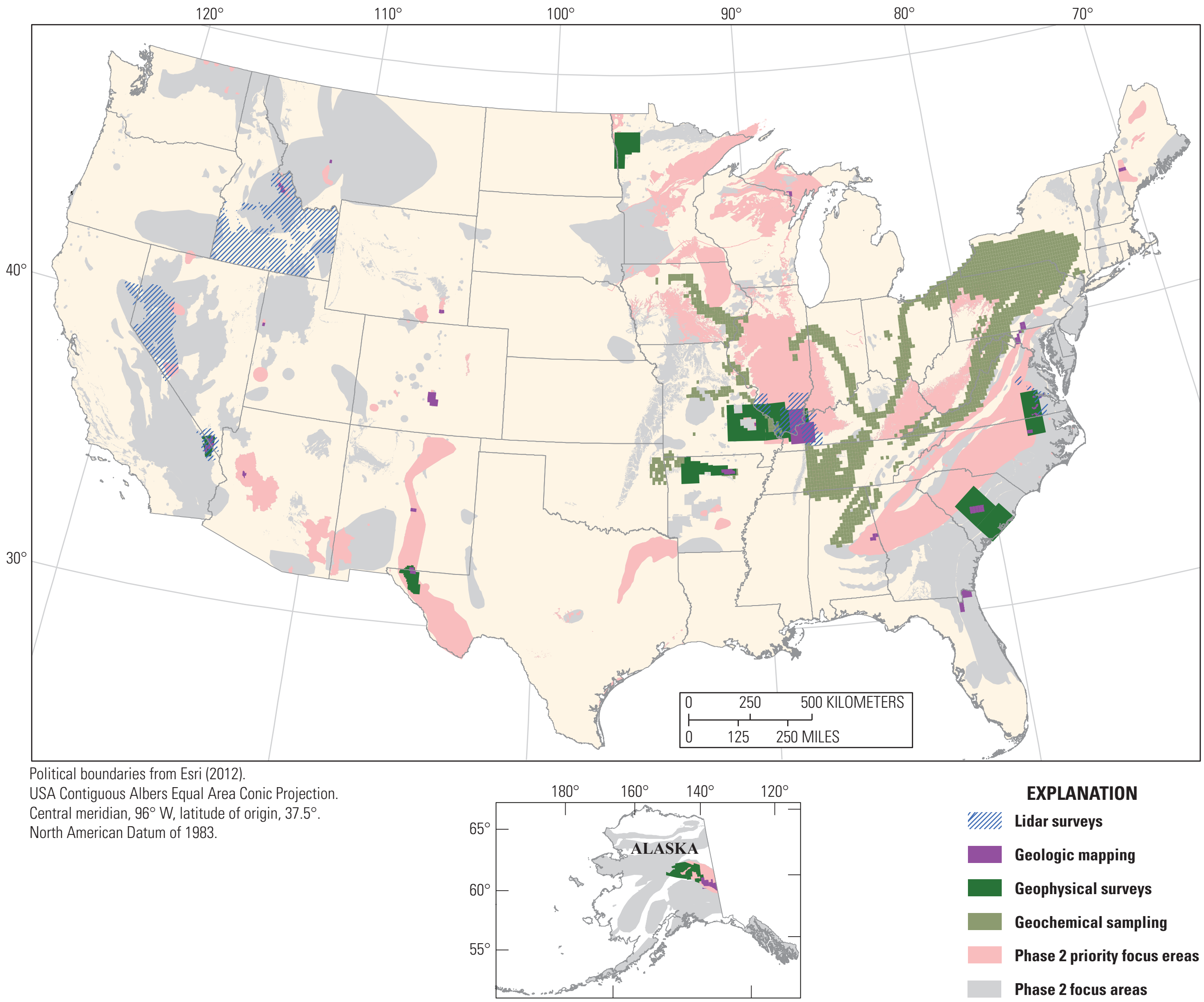
Many of the phase 2 critical minerals have not been produced in the United States for more than 50 years. No graphite, niobium, tantalum, tin, or tungsten was mined in the United States in 2019 (table 1). Aluminum, cobalt, lithium, PGEs, and REEs were produced from only one or two areas of the country. Titanium, the exception, has been produced as ilmenite from heavy-mineral-sands operations along the southeastern United States extending from Florida to Virginia for many decades.

Future supplies of critical mineral resources may be identified in extensions of mined deposits and in resources of other commodities. Critical minerals may be recovered from existing processing facilities and mine waste. Some may derive from new discoveries. Major discoveries of critical minerals in other countries led to closure of mines and diminished domestic exploration in the second half of the 20th century. Higher ore grades, larger tonnages, lower production costs, and foreign subsidies in other countries are additional factors that diminished domestic mining. For example, the Mountain Pass Mine in California was the leading world producer of LREEs until its output was exceeded by production in China (mostly from Bayan Obo) in about 1993 (Castor and Hedrick, 2006). Similarly, discovery of major tungsten skarn deposits in China and Canada led to closure of mines in the United States.

This study delineated 421 focus areas within the conterminous United States, 1 in Hawaii, and 2 in Puerto Rico. Consideration of these focus areas led to identification of more than 60 areas for new data acquisition for a variety of mineral systems. A subset of those areas was then prioritized for allocation of funds through Earth MRI to initiate new projects for phase 2 critical minerals (fig. 15). Identification of PGEs and cobalt in mafic magmatic systems, for example, would benefit from new aeromagnetic data, especially in covered areas of the midcontinent region.

The 74 focus areas for Alaska are described by Kreiner and Jones (2020) and included in the data release by Dicken and Hammarstrom (2020). The Yukon-Tanana area in eastern Alaska is the priority area for new data acquisition in phase 2 because of its multiple mineral systems, which may host many critical minerals (fig. 15).

This first national-scale compilation of focus areas for potential domestic resources of some critical minerals represents an initial step in addressing domestic critical mineral needs by identifying and prioritizing areas for new data acquisition. Some focus areas include active or historical mines, prospects, or exploration project areas that are known to contain critical minerals. Other focus areas are more speculative but warrant further study. The focus areas are broadly defined and do not necessarily contain resources that would be economic to develop in the reasonably foreseeable future. These focus areas do, however, outline areas where acquisition of new data could foster exploration, development of new extraction methods, and evaluation of potential domestic critical mineral resources.



Political boundaries from Esri (2012).
USA Contiguous Albers Equal Area Conic Projection.
Central meridian, 96° W, latitude of origin, 37.5°.
North American Datum of 1983.

Figure 15. Map showing of phase 2 focus areas, priority areas, and areas selected for new geological mapping, geophysical surveys, geochemical sampling, and lidar acquisition in the conterminous United States and Alaska.

Conclusions

The mineral systems and deposit types for phase 2 minerals that are most likely to provide domestic resources in the foreseeable future include sulfide deposits in mafic magmatic systems for PGEs and cobalt, placers for titanium, and skarns associated with various porphyry systems for tungsten. Potential sources of domestic lithium include lacustrine evaporites that host lithium brines and clays and pegmatites that contain spodumene. Magmatic REE systems, especially carbonatites such as the Elk Creek deposit in Nebraska, are the most likely deposit type to contain significant domestic niobium resources. In terms of tonnages and ore grades, deposits associated with carbonatites and peralkaline rocks, iron oxide-apatite deposits, and monazite-bearing placers are the likely potential sources for newly developed domestic REE deposits (Hammarstrom and Dicken, 2019). Phosphate-rich occurrences also represent significant potential sources of REEs.

Other potential sources of critical mineral resources include mine waste derived from the processing of various deposit types. Mine waste compositions are rarely reported; however, processed tailings represent huge volumes of beneficiated material that could represent untapped resources provided that suitable technology and economic incentive for recovery exists. For example, mine waste and tailings in the iron mining districts of upstate New York host significant REE resources (Taylor and others, 2019). Apatite, monazite, and xenotime in the tailings at the Pea Ridge iron deposit, Missouri, are also being investigated as potential sources of REEs. Tin (cassiterite) and tungsten (wolframite) were produced from mine tailings at the Climax porphyry molybdenum deposit. Significant tungsten resources remain in closed or abandoned mines in Montana, Idaho, California, and throughout the Great Basin in tungsten skarn deposits associated with porphyry Cu-Mo-Au systems.

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Appendix 1. Mineral Systems Framework

Appendix 1 includes this explanatory information and a link to an external file for table 1 of Hofstra and Kreiner (2020), which contains the mineral systems framework adopted for the Earth Mapping Resources Initiative (Earth MRI). For completeness, references cited in that table are listed in the section of this appendix titled "References Cited in Table 1 of Hofstra and Kreiner (2020)." See "Table Structure" section of Hofstra and Kreiner (2020, p. 6) for an explanation of the table content. In particular, critical minerals that have actually been produced from the deposit type are highlighted in bold type, whereas those that are enriched in the deposit type, but have not yet been produced, are listed in italics.

The table can be accessed at https://pubs.usgs.gov/of/2020/1042/ofr20201042_table1.pdf

The external file is best viewed by using high magnification (200 to 400 percent of the original size) of the Portable Document Format (PDF) file. Otherwise, the table can be plotted out on large format paper or viewed as the version of table 1 incorporated into the body of the report by Hofstra and Kreiner (2020).

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For more information concerning this report, please contact:
Mineral Resources Program Coordinator
U.S. Geological Survey
913 National Center
Reston, VA 20192
Telephone: 703–648–6100
Fax: 703–648–6057
Email: minerals@usgs.gov
Home page: https://www.usgs.gov/energy-and-minerals/mineral-resources-program

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