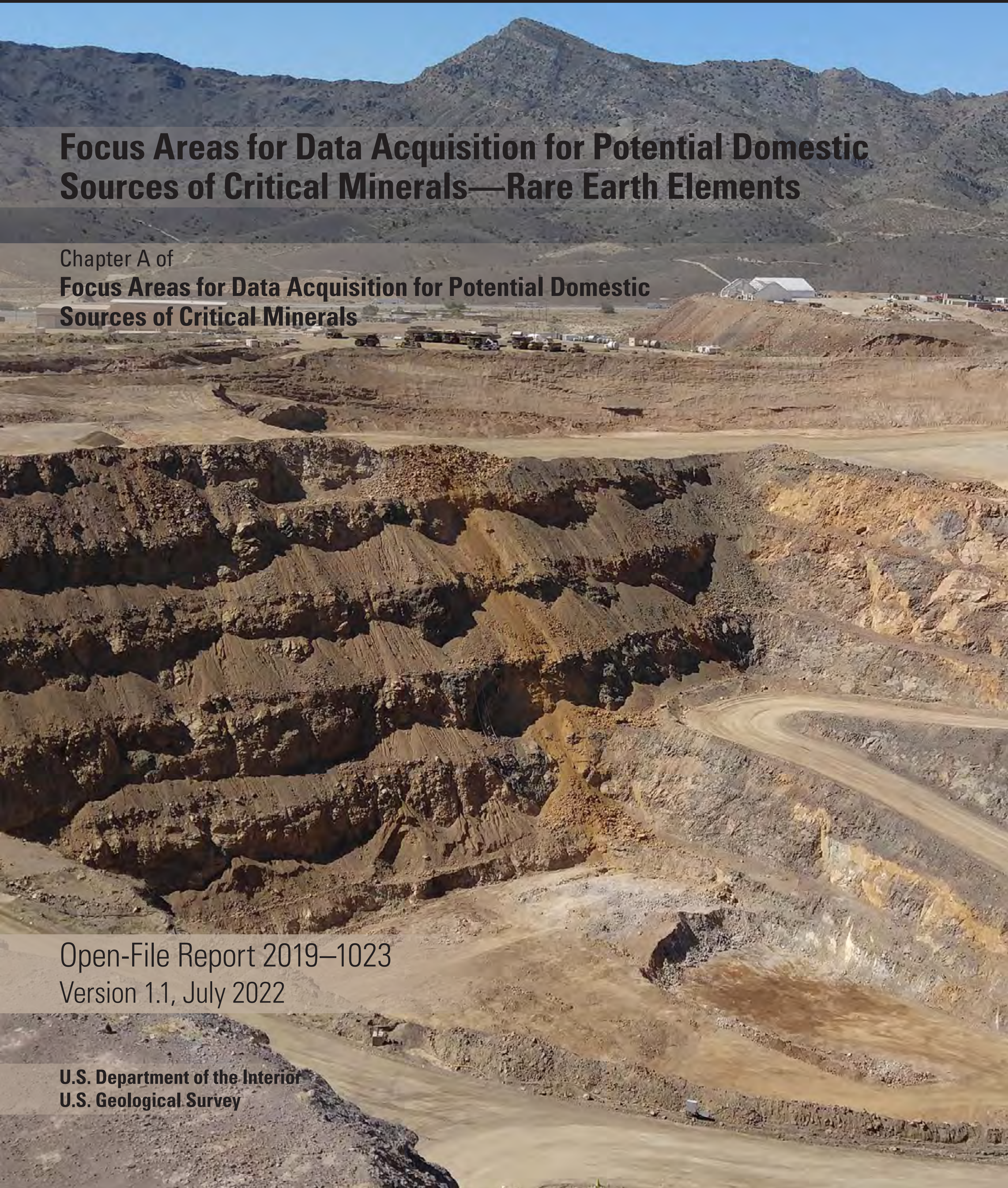

Focus Areas for Data Acquisition for Potential Domestic Sources of Critical Minerals—Rare Earth Elements

Chapter A 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: The Mountain Pass Mine, southeastern California, June 2018; view to the southwest. The ore body, called the Sulphide Queen deposit, is a large tabular carbonatite intrusion, thought to be the largest deposit containing rare earth elements in the United States. The deposit was discovered in 1949. Mining of the deposit began in 1952, and production was nearly continuous until 2002, resumed from 2012 to 2015, and began again in 2017 under new ownership. Photograph by B.S. Van Gosen, U.S. Geological Survey.

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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.

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Mass	
metric ton (t)	1.102	ton, short (2,000 pounds)
million metric tons (Mt)	1.102	million short tons

Abbreviations

ADGGS	Alaska Division of Geological & Geophysical Surveys
ARDF	Alaska Resource Data File
Ga	giga-annum
GIS	geographic information system
HREE	heavy rare earth elements
IOA	iron oxide-apatite
IOCG	iron oxide-copper-gold
km	kilometer
LLC	limited liability company
LREE	light rare earth elements
MAS/MILS	Mineral Availability System/Mineral Industry Location System
MRDS	Mineral Resources Data System
Mt	million metric tons
N	normality
NURE	National Uranium Resource Evaluation
REE	rare earth element
PO_4	phosphate
USGS	U.S. Geological Survey

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Abstract

Rare earth elements (REEs) are critical mineral commodities for the United States. In response to a need for information on potential domestic sources of REEs in mineral deposits, the U.S. Geological Survey (USGS) identified broad focus areas throughout the conterminous United States and Alaska as a guide for selecting new geoscience research areas. This study was done to support the USGS Earth Mapping Resources Initiative (Earth MRI).

Focus areas are identified in four regions of the United States (Alaska, West, Central, and East) by mineral deposit type. The areas are described in a companion USGS data release that consists of a map in a geographic information system and accompanying tables that document the rationale for each focus area (C.L. Dicken and others, 2019, https://doi.org/10.5066/P95CHIL0). This open-file report describes the methodology that was used to identify focus areas and determine new data acquisition needs. Deposit types that are likely to be of interest for future exploration and development of domestic nonfuel REE resources include deposits associated with carbonatites and peralkaline rocks, iron oxide-apatite deposits, monazite-bearing placers, and REE-enriched phosphorites.

Introduction

The U.S. Geological Survey (USGS) is launching the Earth Mapping Resources Initiative (Earth MRI) in response to a need for information on potential domestic sources of many critical minerals (Day, 2019). This report describes the background data, sources, and methodology used to define broad areas within the United States as focus areas for future geoscience research efforts to search for potential sources of rare earth elements (REEs) in nonfuel deposit types.

The focus areas defined in this report were identified on the basis of existing data. Acquisition of new geologic mapping data, geophysical data, and (or) detailed topographic information within these areas would enable researchers to evaluate the REE potential of these areas and would provide data that could be used in mineral exploration. Focus areas include known REE deposits as well as areas that may have potential REE sources according to our understanding of the geologic characteristics of REE deposits.

A related USGS data release (Dicken and others, 2019) depicts focus areas on a map created from a geographic information system (GIS), provides data tables that summarize what is known about the REE potential of the focus areas, and contains brief descriptions of data gaps that could be filled by data collected through Earth MRI.

Rare-Earth-Element Groups

The 15 lanthanide elements along with scandium and yttrium comprise the rare earth elements (REEs). REEs have important applications in components used in the aerospace, defense, energy, telecommunications and electronic, and transportation sectors of the U.S. economy. China, the top producer and consumer of REEs, supplies about 97 percent of the REEs globally. Several recent studies identify REEs as critical to the United States due to their high importance in technologies and high risk for supply disruptions (Van Gosen and others, 2014, 2017; Fortier and others, 2018; Gambogi, 2018; U.S. Department of the Interior, 2018). 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, 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. The HREE group is particularly important to emerging technologies in so-called green energy, defense, and electronic industries. HREE-enriched deposits are the primary supply issue for the United States; most of the known domestic REE deposits are enriched in LREEs.

Rare-Earth-Element Mining in the United States

REE mineral occurrences are widely distributed throughout the United States. However, only one U.S. deposit, the Mountain Pass Mine in California, is currently producing REEs; it has been the only significant producer of REEs in the United States ever. Mining of the deposit began in 1952, and production was nearly continuous until 2002, resumed from 2012 to 2015, and began again in 2017 under new ownership. The mine produced concentrates of the REE mineral bastnaesite until production ceased in 2002 due to a combination of environmental and economic issues (Long and others, 2010; Van Gosen and others, 2017). The Mountain Pass Mine 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). In 2015, Molycorp Inc., placed the Mountain Pass Mine under "Care and Maintenance" status. As of 2017, the Mountain Pass Mine was under new ownership by MP Mine Operations LLC. In 2019, the mine is the sole U.S. REE deposit in production. Advanced exploration projects for REEs have occurred in Wyoming, Nebraska, Texas, and Alaska in recent years (Van Gosen and others, 2017).

REEs can be a primary target commodity, as at Mountain Pass Mine, or they can be produced as a byproduct or coproduct of other commodities, such as sedimentary phosphate minerals, provided that suitable technologies are available for economic extraction. The size and concentration of HREEs in some unmined sedimentary phosphorites are much larger than the world's richest HREE deposits and could be developed as stand-alone REE deposits, with phosphate (PO_4) as a byproduct (Emsbo and others, 2015, 2016).

Geologic Framework for REE Focus Areas

Although the REEs are not rare in terms of crustal abundance, ore-grade concentrations of REEs are uncommon and are restricted to discrete types of mineral deposits that reflect distinct geologic processes. Individual mineral deposits are small parts of much larger mineralizing systems that require a metal source, energy to drive the system, fluids, and fluid pathways to carry the metals to a trap where conditions must be appropriate to deposit ore minerals. Large-scale features, such as lithospheric architecture, age and nature of basement rocks, and geodynamic settings can be first-order controls on the distribution of deposits by providing a source of metals and the energy to drive the mineralizing system. Regional- and local-scale lithologies and structures as well as degrees of uplift and erosion can affect fluid flow to sites of deposition and preservation of deposits.

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 that may occur within the United States are grouped in mineral systems associated with different geologic processes (table 1). 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. Recognition of 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.

The deposit types listed in table 1 reflect the geologic settings in which known economic or potentially economic REE deposits occur throughout the world (Van Gosen and others, 2017). In addition to these bedrock and placer sources of REEs, U.S. coals and lignites represent potential sources of REEs. No focus areas are delineated for REE-bearing minerals related to energy resources because this study is limited to potential nonfuel sources. However, recent studies suggest that lignite and lignite-related materials in North Dakota (Laudal and others, 2018) and bituminous coals in the Appalachian region of Kentucky, Alabama, West Virginia, Pennsylvania, and Virginia may hold promise as REE sources (Lin and others, 2018).

Data Sources

Rare-Earth-Element Provinces

Olson and Adams (1962) compiled a map and pamphlet on thorium and rare earth occurrences in the United States, exclusive of Alaska and Hawaii. Subsequently, Staatz and Armbrustmacher (1981) produced a 1:5,000,000-scale preliminary map of rare-earth provinces in the conterminous United States that identified 20 broad areas or belts of REE occurrences. Their map listed REE deposit types associated with each province and included a preliminary estimate of resource potential (High, Medium, Low, or Unknown) along with an indication of whether available geologic information on the region was adequate or insufficient at the time.

Rare-Earth-Mineral Occurrences

Mineral occurrence data for REEs are available in several databases. A 2018 data release on rare earth occurrences in the United States describes more than 200 districts, mines, and mineral occurrences that are reported to contain substantial enrichments of REEs (Bellora and others, 2018). This compilation, currently the most complete and well-documented publicly available source for rare earth occurrences in the United States, includes resource and production information as well as information on deposit type and references. In addition to point data, the GIS includes polygons showing the outline of deposits, mineral

Table 1. Nonfuel mineral systems and deposits bearing rare earth elements (REEs) that may occur in the United States.

[See Van Gosen and others (2017) for detailed descriptions of these deposit types and examples]

Mineral system	Deposit types	Example
Surficial weathering:		
Physical weathering	Monazite- and xenotime-bearing placers and paleoplacers	Long Valley placer district, Idaho
	Coastal heavy-mineral sands	Grove Cove Spring, Florida
Chemical weathering	Regolith-hosted REEs	No U.S. deposit of this type is known; this type occurs in China.
Epicontinental marine basin	Sedimentary marine phosphate	Crystal Creek, Wyoming; Love Hollow, Arkansas
Magmatic hydrothermal	Climax-type porphyry molybdenum	Climax, Colorado
	Iron oxide-apatite and iron oxide-copper-gold (IOA-IOCG)	Pea Ridge, Missouri
Magmatic	Carbonatites	Elk Creek, Nebraska; Mountain Pass, California
	Alkaline/peralkaline igneous rocks	Bokan Mountain, Alaska
	Pegmatite	Little Friar Mountain, Virginia
	REE-bearing veins	Lemhi Pass, Idaho
Metamorphic	Gneiss-hosted REEs	Music Valley, California

districts and mining districts, extent of placer workings, and mining-related surface workings.

Older, generally less well documented information is available in the online Mineral Resources Data System (MRDS, https://mrdata.usgs.gov/mrds/). 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 the 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. For Alaska, descriptions of mines, prospects, and mineral occurrences in the Alaska Resource Data File (ARDF, https://ardf.wr.usgs.gov/index.php) are published for individual U.S. Geological Survey 1:250,000-scale quadrangles in Alaska. These descriptions were compiled from published literature and from unpublished reports and data from industry, the U.S. Bureau of Mines, the USGS, and other sources.

Other general data sources include reports on the principal REE deposits of the United States (Long and others, 2010) and a chapter on REEs in the 2017 USGS compilation on critical minerals in the United States (Van Gosen and others, 2017). Selected references for each focus area are included in the tables in the data release accompanying this report (Dicken and others, 2019).

Geologic Maps

A compilation of State-scale (1:250,000- to 1:500,000-scale) geologic maps for the conterminous United States (Horton, 2017) provides data on the distribution of certain lithologies that could be associated with REE deposits. For Alaska, the primary geologic map used was the digital geologic map of Alaska (Wilson and others, 2015) and accompanying databases; these are a compilation and interpretation of published and unpublished 1:250,000-scale and limited 1:500,000- to 1:63,360-scale maps. References for more detailed maps used to delineate each focus area are listed in the tables in the data release accompanying this report (Dicken and others, 2019).

Other Studies

A GIS-based study of Alaska identified areas that have potential for selected critical minerals (Karl and others, 2016). The study included an evaluation of estimated resource potential and certainty for deposits associated with peralkaline to carbonatitic igneous intrusive rocks that could contain concentrations of rare earth elements-thorium-yttrium-niobium (uranium-zirconium) [REE-Th-Y-Nb(-U-Zr)]. A data-driven GIS-implemented method was used to systematically and simultaneously analyze geoscience data from multiple geospatially referenced datasets using individual subwatersheds (having 12-digit hydrologic unit codes) as the spatial unit of classification. The final map output shows estimated relative potential (High, Medium, Low, Unknown) and relative certainty (High, Medium, Low) of the estimate for each subwatershed. Accompanying tables describe the data layers used to score favorability for the presence of each mineral deposit group, the values assigned for specific analysis parameters, and the relative weighting of each data layer that contributes to estimated measures of potential and certainty. Primary datasets used include the Alaska Geochemical Database, Version 2.0 (AGDB2); the digital "Geologic Map of Alaska"; the Alaska Resource Data File (ARDF); and aerial gamma-ray surveys flown as part of the National Uranium Resource Evaluation (NURE) program by the U.S. Department of Energy. These datasets are available on the USGS Mineral Resources Online Spatial Data website at https://mrdata.usgs.gov/. Another source used was the Alaska Division of Geological & Geophysical Surveys (ADGGS) web-based geochemical database (DGGS Staff and others, 2017).

Methods

Delineation of Focus Areas

Focus areas with the potential to host nonfuel REE deposits in the United States were delineated by regional teams of USGS geologists using a variety of data sources and approaches. The work was conducted by four teams for the U.S. regions shown in figure 1: Alaska, West, Central, and East. Hawaii was considered unlikely to have significant REE deposits because the geology is not permissive for known types of REE deposits. Each team provided outlines for each focus area within their region (fig. 2). Note that some broad focus areas cross regions. Focus area outlines were compiled in a GIS (Dicken and others, 2019). In some regions, a linear feature was provided to illustrate a trans-lithospheric structure or boundary that could represent a control on the distribution of REE deposits; for example, the Great Lakes Tectonic Zone is a Neoarchean structure that intersects the Midcontinent Rift in the Northern Midcontinent region.

Some focus areas, such as those for potentially REE-bearing phosphate deposits, are based on selection of geologic map units that include a permissive host rock type by age for a particular type of REE deposit. Others are based on generalized outlines of known mining districts or mineral belts, distributions of observed occurrences, polygons of mining areas and surface features (Bellora and others, 2018), and, in some cases, geochemical and (or) geophysical anomalies that could be associated with deposits. In the Midcontinent region of the central United States, where most of the undiscovered resources are likely to lie at depth beneath Paleozoic cover rocks, existing aeromagnetic data aided the delineation of focus areas. Mapped alkaline intrusive complexes and carbonatite complexes, such as the Magnet Cove intrusion in Arkansas, represent focus areas. Many discrete rare earth occurrences are shown with a 15-kilometer (km) buffer to highlight the area of interest; these occurrences include deposits, prospects, or showings. For Alaska, the focus areas outline groups of watersheds that had a high prospectivity ranking in the statewide data-driven study (Karl and others, 2016). In the East, very generalized belts of granitic rocks that could potentially host in situ regolith REE deposits are delineated by age.

All of the REE mineral occurrences (deposits, prospects, showings) included in the USGS Mineral Deposit Database project (USMIN) data release by Bellora and others (2018) are included in focus areas. In some cases, the polygons that outline districts or surface workings as derived from the data release (Bellora and others, 2018) are the basis for the focus area. In other examples, such as the Climax porphyry molybdenum mine in Colorado, the single point location is surrounded with a 15-km buffer to identify the general area as a region of interest.

Focus areas are outlined solely on the basis of geology, regardless of political boundaries. Therefore, areas may include Federal, State, Tribal, and private lands, which may or may not be open to exploration and mining activities. Many areas cross State lines, and some individual focus areas are composed of multiple, geographically discrete subareas.

Documentation of Focus Areas and Data Needs

The rationale for delineating each focus area is documented in a table in the accompanying data release (Dicken and others, 2019). The tables are constructed by using a template that summarizes existing data on past production and exploration, identified resources, REE mineral occurrences, deposits, status of geologic mapping, geochemical and geophysical data, and general comments and selected references (table 2). The comments section may include subjective rankings of the relative significance of the focus area for hosting REEs. The last section of the template lists specific data needs that could be addressed by Earth MRI to better evaluate each focus area for REE potential.

Some focus areas have deposits with identified REE resources that were mined in the past, whereas other focus areas have no known REE deposits but contain geologic characteristics that are broadly permissive for undiscovered deposits. Airborne geophysical data are especially helpful in identifying buried iron oxide-apatite (IOA) and (or) iron oxide-copper-gold (IOCG) targets in the Midcontinent due to the associated magnetite content of these deposit types.

Phosphate deposits throughout many areas of the United States are enriched in REEs and have 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 light and heavy REEs.

Regolith-hosted REE deposits are an easily mined source of REEs in China, India, and Brazil. Consequently, U.S. focus areas are outlined that include highly weathered granitic rocks having a composition similar to the granites in China and containing comparable amounts of REEs (Foley and Ayuso, 2015).

Detailed geologic mapping is needed to further refine focus areas for REE deposits, especially in Alaska. Table 3 summarizes geophysical methods that may be best suited to identifying REE-bearing mineral systems and deposits. Lidar would be helpful for seeing through vegetation, identifying sand deposits that could host monazite-bearing stream placers, and tracing lineaments and other surface features in some parts of the country.

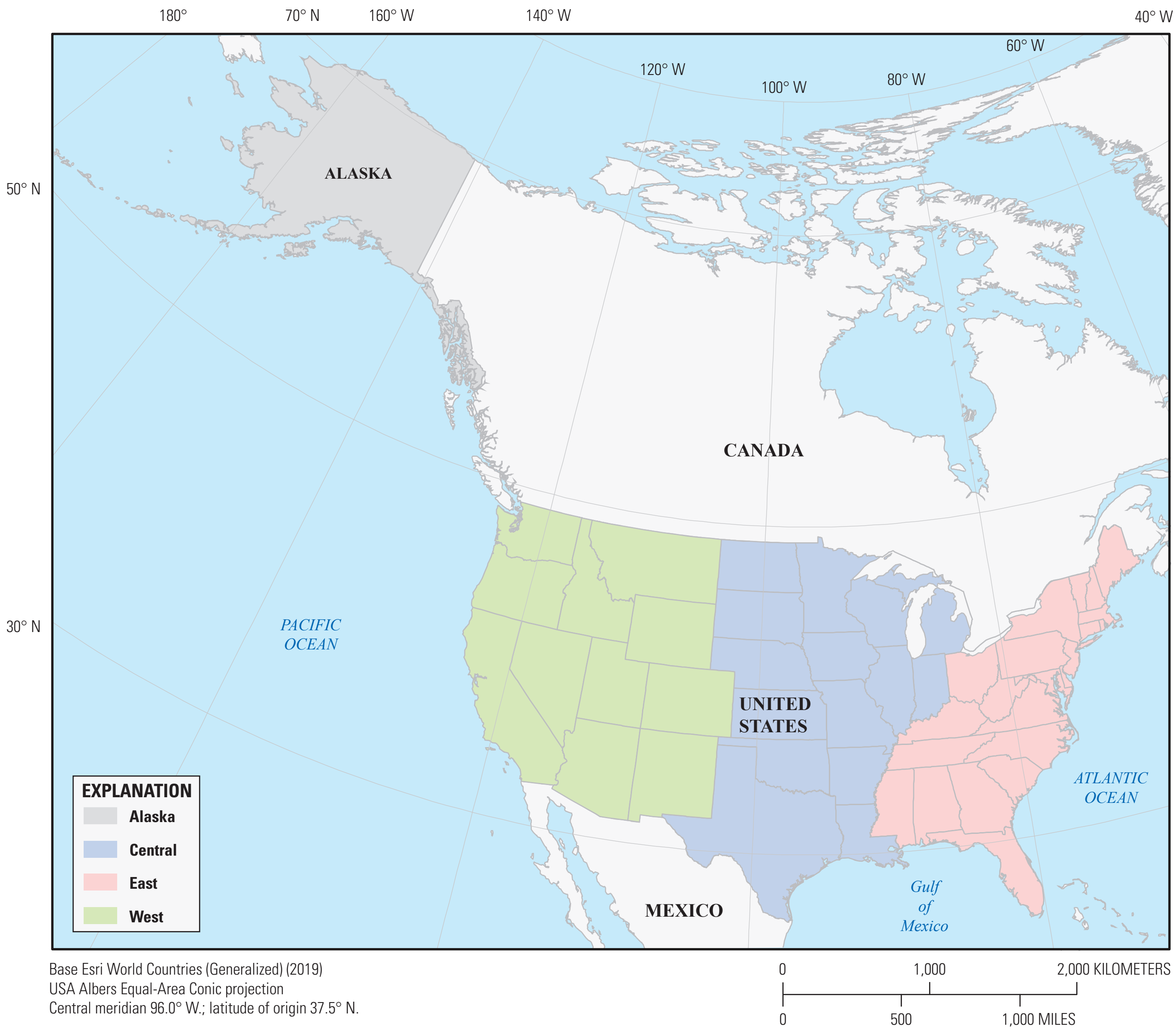

Figure 1. Focus area regions in the conterminous United States and Alaska for rare earth elements in nonfuel deposit types.

Figure 2. Focus areas for nonfuel, REE-bearing mineral deposit types in four U.S. regions. For examples of deposits of these types, see table 1. IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; REE, rare earth element. Modified from Dicken and others (2019).

Table 2. Factors used in the template to delineate U.S. focus areas having the potential to contain sources of rare earth elements (REEs) 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
Mineral system	Select from table 1 of this report
Deposit type(s)	Select from table 1 of this report
Commodities	Mineral commodities associated with the focus area
Identifier (REE_Region_###)	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 that cover the area	Estimate of the percent of the focus area covered by geologic mapping at different scales; cite specific references if applicable
Geophysical data that cover the area	Types and quality of available data (aeromagnetic, gravity, radiometric, other)
Favorable rocks and structures	Lithostratigraphic suitability for REE deposits; structures that may control mineralization
Deposits	Name deposits within the focus area that have identified resources or past production
Evidence for REE from mineral occurrences	Summarize REE occurrences, if any, from USMIN, MRDS, ARDF, or other databases
Geochemical evidence	Stream sediment, rock, or soil indications of REEs or associated commodities
Geophysical evidence	Data that may indicate buried intrusions, extensions of known mineralization, structural controls, or presence of REE minerals (radiometric data)
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	Regional team authors
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

Table 3. Geophysical methods for identifying U.S. mineral systems and deposits that could contain rare earth elements (REEs).

[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. EM, electromagnetic; IP, induced polarization]

Mineral system	Deposit types	Geophysical method
Surficial weathering:		
Physical weathering	Monazite- and xenotime-bearing placers and paleoplacers or coastal heavy-mineral sands	Radiometric methods are excellent for deposits that lie at or near the surface. Magnetic and other methods are helpful for geologic framework. EM methods (especially IP) can be important to excellent; cost-effectiveness is a concern.
Chemical weathering	Regolith-hosted REEs	Radiometric and magnetic methods are important for geologic framework.
Epicontinental marine basin	Sedimentary marine phosphate	Radiometric methods are important if deposits are at or near the surface. Magnetic and other methods are helpful for geologic framework.
Magmatic hydrothermal	Climax-type porphyry molybdenum	Magnetic and gravity methods are helpful and radiometric methods are sometimes helpful if deposits are at or near the surface. EM methods (especially IP) are excellent for imaging sulfides or alteration products in the upper hundred meters.
	Iron oxide-apatite and iron oxide-copper-gold (IOA-IOCG)	Magnetic methods are excellent; radiometric methods are excellent if deposits are at or near the surface. Gravity methods are important (if cost-effective).
Magmatic	Carbonatites	Magnetic methods are excellent; radiometric methods are excellent if deposits are at or near the surface. Gravity methods are important (if cost-effective).
	Alkaline/peralkaline igneous rocks	Magnetic methods are excellent; radiometric methods are excellent if deposits are at or near the surface. Gravity methods are important (if cost-effective).
	Pegmatite	Magnetic methods may be important if significant magnetization contrasts between pegmatite and host rock exist. The same holds true for gravity and density methods. Magnetic, gravity and radiometric methods are helpful for geologic framework.
	REE-bearing veins	Radiometric methods are important if deposits are at or near the surface.
Metamorphic	Gneiss-hosted REEs	Magnetic, gravity and radiometric methods may be helpful for geologic framework.

Discussion

The focus areas outlined throughout the United States may or may not host future economically recoverable REE resources. Further evaluation of potential REE resources requires research and acquisition of new data. Carbonatites are the primary source of REEs on a global scale. The only currently active REE mine in the United States is the carbonatite deposit at Mountain Pass, California. Advanced exploration projects that have reported estimates of REEs in the United States include carbonatite deposits (for example, Bear Lodge, Wyoming; Elk Creek, Nebraska) and deposits in peralkaline igneous rocks at Bokan Mountain, Alaska, and Round Top, Texas (Van Gosen and others, 2017). IOCG and IOA deposits are another potential type of source of REEs for the United States, particularly under cover in the Midcontinent region, where new geophysical data would be especially beneficial. More than a century ago, monazite-bearing placers represented a major source of domestic REE production. Several focus areas outline placer districts in the coastal sediments of the southeastern United States and in river deposits in Idaho and Alaska.

Some of the deposit types listed in table 1 have produced REEs in the past or contain identified resources. Others, such as phosphate rock and regolith-hosted REE types, are potential new sources of REEs that could potentially be readily recovered, in contrast to some of the more complex magmatic ores that pose technological challenges for beneficiation and REE recovery. An evaluation of the REE potential of U.S. phosphorites (phosphate rock) by Emsbo and others (2015, 2017) showed that concentrations of REEs are consistent across individual phosphate beds and that phosphate rock currently mined in the United States could produce a significant amount to meet the global demand for REEs as a byproduct. Regolith-hosted deposits (ion-absorption clay deposits), such as those mined for heavy REEs in China, may have formed in parts of the southeastern United States where granitic rocks of appropriate compositions have been exposed to deep weathering (Foley and Ayuso, 2015).

Other potential sources of byproduct REEs and other critical minerals include mine tailings from a variety of deposit types. Unfortunately, tailings compositions are rarely reported; however, tailings represent huge volumes of beneficiated material that could represent potential untapped resources provided that suitable technology for recovery exists. For example, REE-bearing hydrothermal apatite and titanium (another critical mineral) in rutile, generally occur in porphyry copper deposits. Although porphyry copper-rich intrusive rocks can contain from about 70 parts per million total REEs to occasionally as much as 200 parts per million total REEs, the volumes of tailings produced are huge. The San Manuel porphyry deposit (40 km north-northeast of Tucson, Arizona), alone, has probably in excess of 500 million metric tons (Mt) of tailings, a potential candidate for secondary recovery of accessory minerals, such as rutile and apatite, or other minerals that could host REEs or other critical minerals. Apatite and monazite in the tailings at the Pea Ridge iron deposit, Missouri, are also being investigated as potential sources of REEs.

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. Carbonatites, such as those at the Mountain Pass Mine, are high grade in terms of LREEs but are nearly always highly depleted in HREEs, and as such, do not address the U.S. demand for HREEs. The gneiss-hosted REE deposit at Music Valley, California, formed 1.4 billion years ago (at 1.4 Ga), shares some features with Mountain Pass, and occurs in a northwest-trending belt that is 3 by 9 km in extent, that is associated with the edges of prominent geophysical anomalies, and that may be analogous to the geologic setting of carbonatite volcanoes in the East African Rift. Better quality geophysical data and detailed geologic mapping in the area could better define the REE potential of the area. While some peralkaline deposits are HREE enriched (for example, Bokan Mountain, Alaska), many have associated metallurgical issues, such as complex mineralogy that makes economic extraction challenging and high thorium and uranium contents.

Globally, HREEs are mainly produced from the low-grade South China clay deposits. These deposits are easy to mine, have relatively simple metallurgy because REEs are readily removed from the clays by an ion-exchange acid-leach technique, and are worked with cheap labor costs and minimal environmental restrictions.

Phosphate-rich occurrences also represent attractive sources of REEs. For example, samples from over 100 square kilometers (km^2) of the 1.5-meter-thick Ordovician phosphorite horizon at Love Hollow, Arkansas, have remarkably homogenous REE abundances with concentrations comparable to those of the Bokan Mountain, Alaska, deposits. Emsbo and others (2015) estimated a contained 235 Mt of phosphate rock with 1.3 Mt of extractable total REEs at Love Hollow, Arkansas, of which 0.37 Mt are HREEs, which is nearly twice the HREE content of the South China clays and 60 times that contained in the Bokan Mountain deposit. This potential resource occupying an area of 100 km^2 represents a small fraction of the horizontal horizon that can be traced at or just below the surface over an area of 2,000 km^2 of northern Arkansas, where it likely maintains a consistent thickness and grade. Importantly, experiments suggested that dissolution of the fluorapatite mineral francolite ($Ca_5(PO_4, CO_3)_3(F,O)$, where REEs substitute for Ca) from phosphate ores using dilute H_2SO_4 (0.4 normality [N]) and HCl (0.5 N) extracted 100 percent of the contained REEs (Zhang and others, 2006). This extraction efficiency is unlike the difficulties encountered in extracting REEs from traditional REE deposits.

Priority Data Needs

New geologic mapping and acquisition of airborne geophysical data focused on REE-hosting mineral systems may show that other, perhaps unrecognized, deposit types represent potential domestic sources of REEs. Geophysical data would be especially useful for tracing the Midcontinent Rift system, which is known to contain a variety of deposit types, including small uranium-REE-niobium-bearing carbonatite bodies, under cover in the southern part of the rift system.

Priority should be given for new surveys that address data gaps that may better define potential domestic sources of REEs in sedimentary marine phosphate deposits, carbonatites, deposits associated with peralkaline igneous rocks, and modern placer or paleoplacer deposits, particularly deposits that host HREEs.

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