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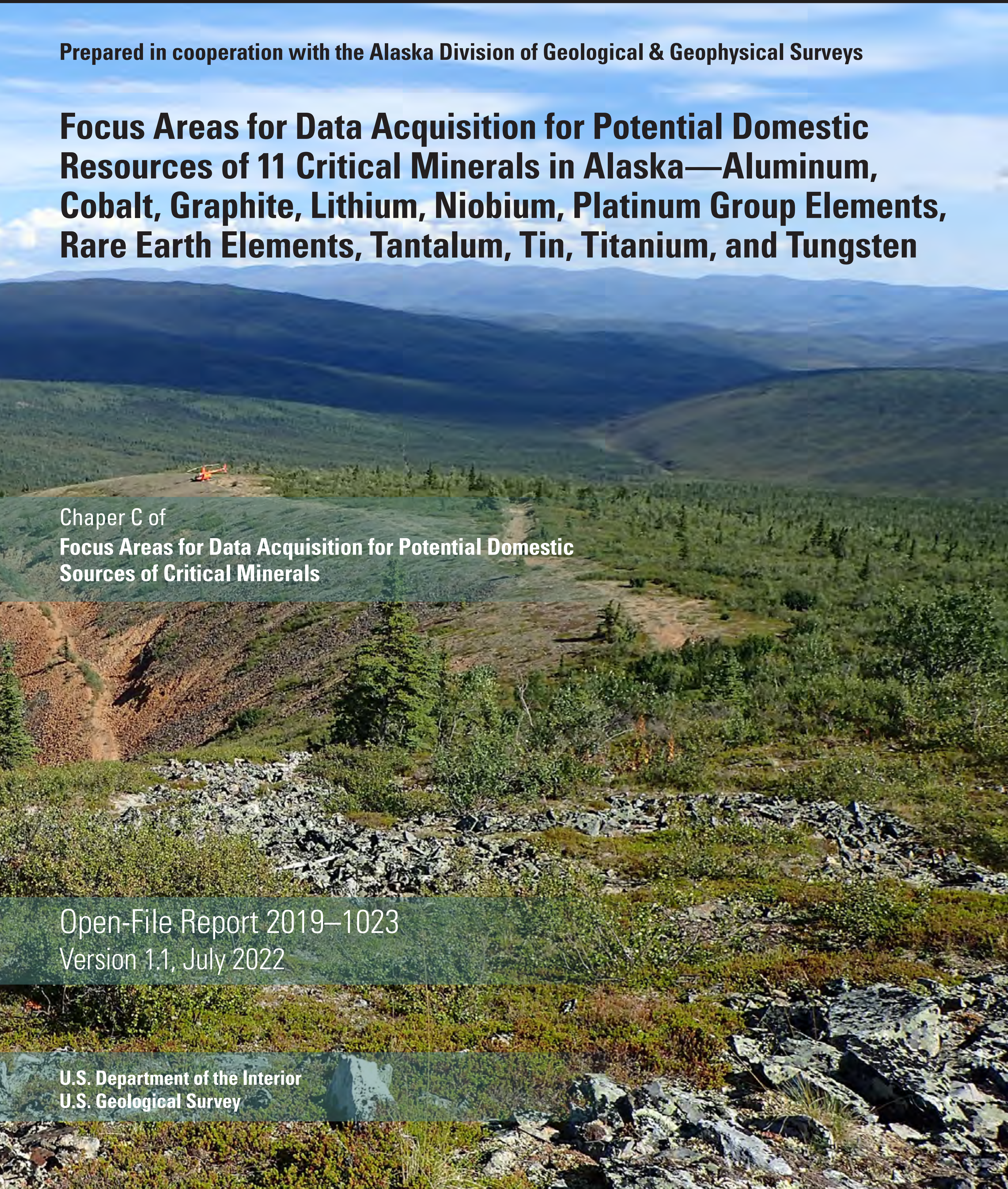
Prepared in cooperation with the Alaska Division of Geological & Geophysical Surveys

Focus Areas for Data Acquisition for Potential Domestic Resources of 11 Critical Minerals in Alaska—Aluminum, Cobalt, Graphite, Lithium, Niobium, Platinum Group Elements, Rare Earth Elements, Tantalum, Tin, Titanium, and Tungsten



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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: View looking east-northeast towards Yukon Territory, Canada, with McCord Creek in the foreground, and showing Late Cretaceous Taurus porphyry prospect that contains copper-, molybdenum-, and gold-bearing mineralization with associated critical mineral enrichments including rhenium and arsenic, Yukon-Tanana upland in eastern interior Alaska. Photograph by Douglas Kreiner, U.S. Geological Survey, Research Economic Geologist, August 8, 2017.

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By Douglas C. Kreiner and James V. Jones III

Chapter C of
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U.S. Department of the Interior
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U.S. Department of the Interior
DAVID BERNHARDT, Secretary

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James F. Reilly II, Director

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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

Funding for this work was provided by the Mineral Resources Program within the USGS and the Earth Mapping Resources Initiative. Melanie B. Werdon, Alaska Division of Geology & Geophysics, participated in workshops and provided data to complete the documentation of focus areas in Alaska. We thank USGS colleagues George Case and Benjamin Drenth for their constructive reviews of this report.

Contents

Figures

Tables

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)
	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)

Conversion Factors—Continued

International System of Units to U.S. customary units

Multiply	By	To obtain
	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

AGDB	Alaska Geochemical Database
ARDF	Alaska Resource Data File
Earth MRI	Earth Mapping Resources Initiative
GIS	geographic information system
HREE	heavy rare earth elements
IOA	iron-oxide apatite
IOCG	iron-oxide copper gold
MRDS	Minerals Resources Data System
REE	rare earth elements
PGE	platinum group elements
ppm	parts per million
USGS	U.S. Geological Survey
USMIN	Mineral Deposit Database

Chemical Symbols

Ag	silver
Al	aluminum
As	arsenic
Au	gold
Be	beryllium
Bi	bismuth
Co	cobalt
Cr	chromium
Cs	cesium
Cu	copper
Fe	iron
Ga	gallium
Ge	germanium
Hf	hafnium
In	indium
Li	lithium
Mg	magnesium
Mn	manganese
Mo	molybdenum
Nb	niobium
Ni	nickel
P	phosphorus
Pb	lead
Rb	rubidium
Re	rhenium
Sb	antimony
Sc	scandium
Sn	tin
Sr	strontium
Ta	tantalum
Te	tellurium
Ti	titanium
U	uranium
V	vanadium
W	tungsten
Zn	zinc
Zr	zirconium

Focus Areas for Data Acquisition for Potential Domestic Resources of 11 Critical Minerals in Alaska—Aluminum, Cobalt, Graphite, Lithium, Niobium, Platinum Group Elements, Rare Earth Elements, Tantalum, Tin, Titanium, and Tungsten

By Douglas C. Kreiner and James V. Jones III

Abstract

Phase 2 of the Earth Mapping Resources Initiative (Earth MRI) focuses on geologic belts that are favorable for hosting mineral systems that may contain select critical minerals. Phase 1 of the Earth MRI program focused on rare earth elements (REE), and phase 2 adds aluminum, cobalt, graphite, lithium, niobium, platinum-group metals, tantalum, tin, titanium, and tungsten. This report describes the methodology and techniques utilized to define focus areas for future data acquisition in Alaska; the conterminous United States are covered in a separate report.

Definition of focus areas relies on a mineral systems framework that considers geologic features that may influence or control the formation and preservation of a mineral deposit and links the critical commodities to genetically related processes. Mineral systems are therefore larger than any given deposit. Evaluation of these larger systems allows for a broader understanding of how and where critical minerals may move through geologic systems.

Delineation of focus areas in Alaska was informed by statewide geological, geochemical, geophysical, and mineral occurrence datasets that are publicly available. Additionally, previously published prospectivity analyses for six different critical mineral-bearing deposit types help identify focus areas. A total of 74 focus areas prospective for the phase 2 critical minerals that occur in 12 different mineral systems were defined in Alaska. Identified focus areas may be used to guide future geologic, geochemical, and geophysical data in the State of Alaska.

Introduction

The U.S. Geological Survey (USGS) launched the Earth Mapping Resources Initiative (Earth MRI) in response to the need to document the potential for domestic sources of critical minerals (Day, 2019). The purpose of this report is to describe the background data, sources, and methodology used to define the broad focus areas for future data collection (geologic mapping, aeromagnetic and radiometric geophysical acquisition, and geochemical characterization) in Alaska (fig. 1). Data generated from this effort will inform the understanding of the framework geology and mineral resource potential in multiple regions throughout the State that are known or suspected to contain nonfuel mineral systems with associated phase 2 (Al, Co, graphite, Li, Nb, PGE, Ta, Sn, Ti, and W) and /or phase 1 (rare earth elements [REE]) critical mineral enrichments (table 1).

The Alaska focus areas defined in this report were selected based on a mineral systems framework (Hofstra and Kreiner, 2020) and through careful consideration of published and ongoing statewide geospatial prospectivity mapping (Karl and others, 2016; Karl and others, U.S. Geological Survey, written commun., 2020) and other relevant datasets and publications (e.g., Wilson and others, 2015; Granitto and others, 2019; Kreiner and others, in press). Alaska focus areas are necessarily broad because of significant gaps in modern data coverage and quality across such a large, remote, and geologically complex State (fig. 1). Where possible, Alaska focus areas were drawn to include known mineral deposits that contain critical mineral enrichments identified from the

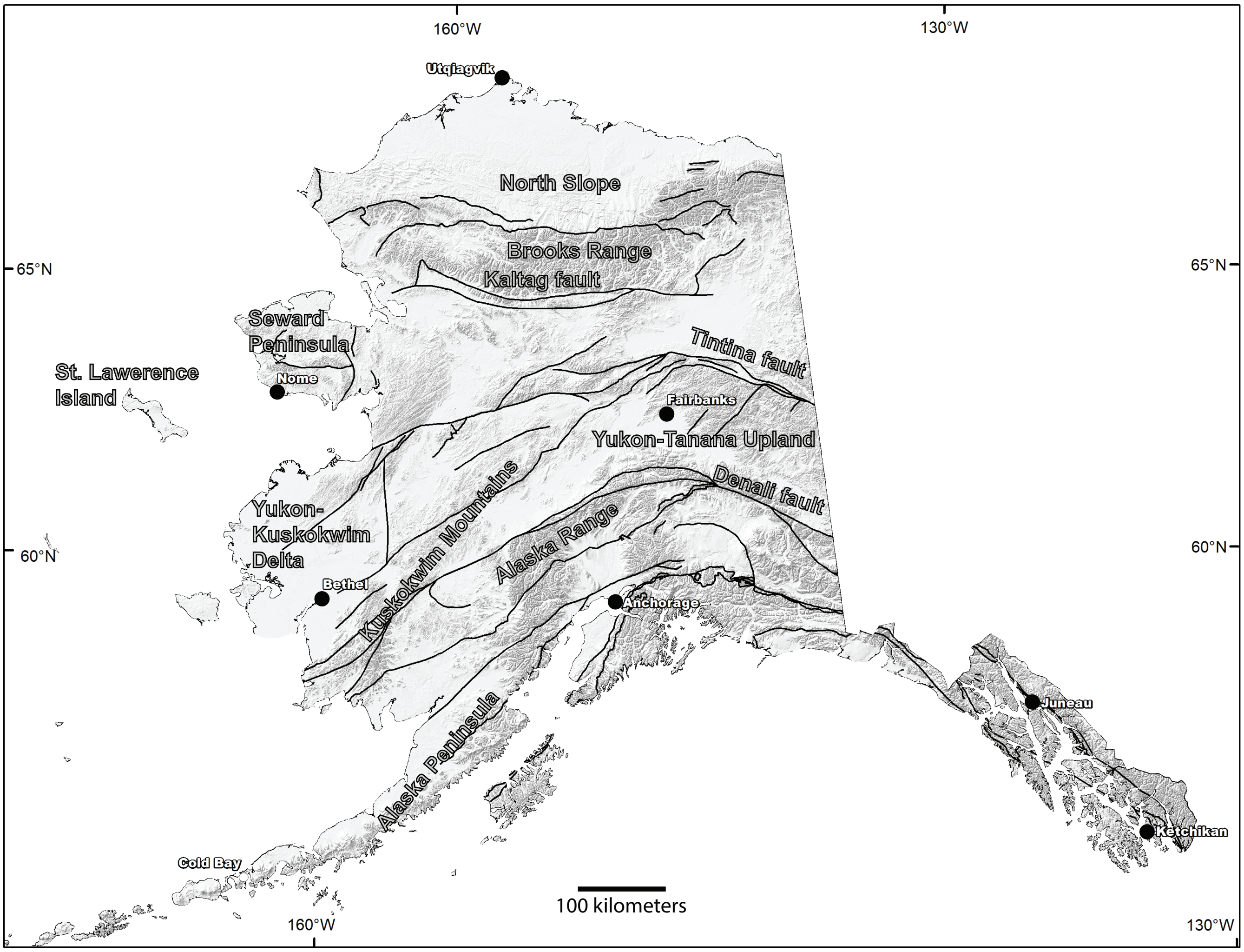

Figure 1. Reference map of Alaska showing geographical distribution of features, population centers, and major faults. Background is a shaded digital elevation model showing areas of high topography in darker shades and low elevation in lighter colors. Major faults are black lines (from Wilson and others, 2015).

Alaska Resource Data File (ARDF; U.S. Geological Survey, 2008). But across the remaining regions of the State without known deposits, broad focus areas were drawn to include areas containing geological characteristics that are prospective for critical mineral enrichments based on current understanding. Many of these areas may lack appropriate data because of a lack of rock exposure (e.g., North Slope and the Yukon-Kuskokwim Delta, fig. 1). In other cases, major fault systems (e.g., Tintina, Denali, and Kaltag faults, fig. 1) may juxtapose drastically different geologic belts, which have been studied in varying levels of detail resulting in disparate geologic data. Acquisition of new geologic data through mapping, geophysical, and geochemical surveys in these focus areas will enhance researchers' ability to evaluate the formation and distribution of prospective mineral systems throughout the State and the systems potential for containing critical mineral resources.

Focus areas and criteria used to define focus areas for the three regions of the conterminous United States are described in a companion report (Hammarstrom and others, 2020). Both the Mineral Resources Data Systems (https://mrdata.usgs.gov/mrds/) and the USMIN mineral deposit database project which has published a series of mineral occurence and data releases on phase 2 critical minerals (Burger and others, 2018; Carroll and others, 2018; Karl and others, 2018, 2019; Bellora and others, 2019) are more complete and more accurate for these regions than the database is for Alaska. Accordingly, delineation of mineral systems and focus areas for phase 2 critical minerals in the conterminous United States relied more heavily on the presence of known mineral occurrences, deposits, or mines that have current or past production. In some cases, though, broader focus areas were developed to encompass

Table 1. Phase 1 and 2 critical minerals.

[Source of U.S. mine production data: U.S. Geological Survey (2020); WH, withheld to avoid disclosing company proprietary data. t, metric ton; kg, kilogram]

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

regions containing mineral systems that have potential for phase 2 critical mineral enrichments in the absence of known deposits.

A related USGS data release (Dicken and Hammarstrom, 2020) depicts focus areas on a map created from a geographic information system (GIS) framework, provides data tables that summarize what is known about the critical mineral potential of the focus areas, contains brief descriptions of data gaps that could be filled by data collected through Earth MRI, and provides information on the extent and quality of the available geophysical and topographic coverages for the United States.

Phase 2 Critical Minerals

Phase 2 critical minerals were selected from the complete list of 35 minerals based on the high net import reliance of the United States combined with an increasing demand beyond the foreseeable domestic production of particular minerals. Earth MRI has focused first on the commodities where a domestic discovery could conceivably reduce the import reliance on foreign sources. A secondary focus of Earth MRI is on the commodities that will require fundamental improvements in recovery and metallurgical processing to increase domestic supply.

Following the selection of the phase 2 critical minerals (table 1), mineral systems were identified (table 2) that contain these commodities as either primary or byproduct phases (e.g., Hofstra and Kreiner, 2020). Alaska contains mineral systems that have the potential to contain all of the phase 2 commodities except for aluminum. Aluminum, which is mined nearly exclusively from bauxite, forms in chemical weathering systems that occur in temperate and equatorial climatic zones. Chemical weathering systems are not presently recognized in any of Alaska's geological belts. Accordingly, aluminum was not considered during the development of the phase 2 focus areas in Alaska.

Table 2. Phase 2 critical mineral systems.

[Abbreviations are defined in the Chemical Symbols list near the front of the report. –, No existing Alaska prospectivity model is available.

Mineral system	Major commodity	Phase 2 critical mineral commodities	Alaska prospectivity model
Basin brine path	Lead, zinc, copper, silver	Cobalt, lithium, PGE, REE, tin	Carbonate-hosted Cu(-Co-Ag-Ge-Ga) deposits
Climax-type	Molybdenum	Aluminum, niobium, tantalum, tin, tungsten	Sn-W-Mo(-Ta-In-fluorspar) deposits associated with specialized granites
IOA–IOCG	Copper, gold	Cobalt, REE	–
Mafic magmatic	Ni, Cu, PGE, chromium	Cobalt, PGE, titanium	PGE(-Co-Cr-Cu-Ni-Ti-V) deposits associated with mafic to ultramafic intrusive rocks
Marine chemocline	Phosphorous, REE	REE, Co	–
Metamorphic	Gold	Graphite, REE, aluminum	–
Magmatic REE	REE	Niobium, tantalum, REE	REE-Th-Y-Nb(-U-Zr) deposits associated with peralkaline to carbonatitic intrusive rocks
Orogenic	Gold	Tungsten, graphite	Reduced-intrusion related and orogenic gold
Porphyry Cu-Mo-Au	Copper, molybdenum, gold, lead, zinc, silver	Aluminum, cobalt, PGE, tungsten	–
Porphyry Sn-W	Tin, tungsten	Lithium, niobium, tantalum, tin, tungsten	Sn-W-Mo(-Ta-In-fluorspar) deposits associated with specialized granites
Placer	Gold, PGE	Niobium, PGE, REE, tantalum, tin, titanium, tungsten	Placer and paleoplacer gold deposits
Meteoric recharge	Uranium, vanadium	cobalt	Sandstone-hosted U(-V-Cu) deposits

Mineral Systems Approach

Mineral systems provide the framework that considers geologic features that may influence or control the formation and preservation of a mineral deposit. Ore deposits, where potentially economic concentrations of critical commodities may occur, represent the culmination of the geologic processes that constitute the mineral system. Mineral systems require the following: (1) an energy driver (e.g., topography, geothermal gradient in the crust, or magma); (2) a source of components (e.g., metals) and fluid (e.g., melts, aqueous fluids, petroleum, and ligands to complex components); (3) transport pathways (e.g., faults, fractures, or permeable lithologic units); and (4) a physical and (or) chemical trap (e.g., mixing of fluids, reduced host rocks, boiling) (Hofstra and Kreiner, 2020). A productive mineral system must incorporate each of these critical criteria to generate a mineral deposit.

Mineral systems generally represent a single and final episode in an otherwise broad geotectonic setting. Systems can be evaluated on larger scales and typically exhibit larger spatial footprints than a single mineral deposit. Furthermore, within a single mineral system, subtle variations in the fluid chemistry, source rocks, ligands, and lithologic setting can result in unique differences in the types of metals that may be transported or trapped in otherwise similar geotectonic settings. These subtle differences are responsible for the presence or absence of critical mineral enrichments as byproducts in a particular system. Critical minerals are rarely the primary mineral commodity being explored and (or) produced, in a mineral system, although exceptions to this general rule include some REEs, PGEs, and graphite deposits. Thus, understanding where, how, and why critical minerals are enriched in mineral systems is essential for more effectively predicting where undiscovered critical mineral resources are more likely to occur (Hofstra and Kreiner, 2020).

Table 2 lists relevant mineral systems that are known or suspected to occur in Alaska together with the major commodities that the systems contain, phase 2 critical mineral commodities that may be present, and the deposit types for which prospectivity has been mapped across the State. Some mineral systems listed in table 2 have not been evaluated in the data-driven, geospatial prospectivity framework. Instead, focus areas for these mineral systems were identified through synthesis of published geological data, recently published review papers (e.g., Kreiner and others, in press), and (or) ongoing geological research.

Data Sources

Delineation of focus areas in Alaska was informed by statewide geological, geochemical, geophysical, and mineral occurrence datasets that are publicly available (Wilson and others, 2015; Granitto and others, 2019). These datasets were developed in anticipation of their utility for geospatially driven geological investigations and mineral resource assessments. USGS researchers have synthesized and queried the available geologic, geophysical, and geochemical datasets that pertain to selected mineral systems, and the researchers modeled the prospectivity for each system type across the State (e.g., Karl and others, 2016; Karl and others, U.S. Geological Survey, written commun., 2020). Attributes describing the prospectivity for each mineral system type are assigned to hydrologic units approximately 100 square kilometers in area that cover Alaska, creating continuous data-driven maps of mineral resource prospectivity across the landscape for key mineral systems. The hydrologic units were chosen as the basis for classification because the units are defined by natural boundaries on the landscape. Stream sediment geochemical data are also a critical component of the prospectivity analysis, and so hydrologic units have a direct connection to sampling strategies and data distribution. The following sections discuss how the various databases were used for modeling and mapping mineral resource prospectivity in Alaska (Karl and others, 2016).

Alaska Geochemical Database

The Alaska Geochemical Database (AGDB) has been released in multiple versions, the most recent is version 3 released in 2019 (Granitto and others, 2019). The database contains geochemical data for more than 396,000 rock, sediment, and soil samples published by the USGS, Atomic Energy Commission National Uranium Resource Evaluation, Alaska Division of Geological & Geophysical Surveys, U.S. Bureau of Mines, and Bureau of Land Management. In addition, mineralogical identification data are available for more than 18,000 pan concentrate samples. The database contains published geochemical data for each individual sample, and the database uses a “best value” approach to return a single value for each element (Granitto and others, 2019). This “best value” approach alleviates confusion where samples have been analyzed multiple times and (or) by different techniques. The “best value” approach uses a hierarchical ranking of analytical techniques for each element to determine the best analytical technique for a given element. Geochemical data form the primary analytical criteria in the prospectivity analysis (Karl and others, 2016). However, some challenges with AGDB data include gaps in spatial data coverage and variations in data quality and availability for some elements.

Alaska Resource Data File

The ARDF is a database that contains information on mineral occurrences, prospects, deposits, and mines across the State of Alaska (U.S. Geological Survey, 2008). The database contains more than 7,000 entries that include placer and lode localities. Each database record contains information about ore mineralogy, alteration mineralogy, structural controls, geologic setting, production, resource estimates (if known), and deposit types (U.S. Geological Survey, 2008). The ARDF is updated to include new and revised records through time; the most recent update was released in 2018 (https://ardf.wr.usgs.gov/index.php).

Digital Geologic Map of Alaska

Alaska has a digital State geologic map that was published at 1:1,584,000 scale and compiled from existing larger-scale mapping across the State (Wilson and others, 2015). The geologic map database was structured to allow for specific queries on rock type, percentage cover of a rock type in an area of interest, structural setting, texture of the rocks (e.g., porphyritic, hypabyssal, and equigranular), composition of rocks (e.g., for igneous rocks), and many other features. The database can be used to build custom maps representing specific lithologic units, rock composition, geologic setting, or age. In addition, an associated radiometric age database contains more than 700 published U-Pb zircon dates and more than 5,300 K-Ar and $^{40}Ar/^{39}Ar$ dates (Wilson and others, 2015).

Delineation of Focus Areas

Data-driven, GIS-based studies in Alaska have already identified prospectivity for numerous ore system types known to contain critical minerals across the State (Karl and others, 2016; Karl and others, U.S. Geological Survey, written commun., 2020). To date, prospectivity models have been developed and published for REE-Th-Y-Nb(-U-Zr) deposits associated with peralkaline to carbonatitic intrusives; placer and paleoplacer gold deposits; PGE(-Co-Cr-Cu-Ni-Ti-V) deposits associated with mafic to ultramafic intrusive rocks; carbonate-hosted Cu(-Cu-Ag-Ge-Ga) deposits; sandstone-hosted U(-V-Cu) deposits; Sn-W-Mo(-Ta-In-fluorspar) deposits associated with specialized granites; and lode gold deposits that include reduced intrusion-related, orogenic and epithermal style systems (Karl and others, 2016; Karl and others, U.S. Geological Survey, written commun., 2020).

For each mineral system type, representative criteria from each of the relevant datasets described in the previous paragraph were mapped across the hydrologic units in the State. Each subwatershed was assigned a score based on the presence or absence of certain geologic, geochemical, mineralogic, or geophysical characteristics. The criteria were developed by critically evaluating the key characteristics of the mineral system(s) that host the deposit type and then evaluating how the available datasets may relate to those characteristics. A point value was assigned for each contributing dataset based on how well a piece of data matches the determined criteria. Scores for each contributing dataset were summed for each subwatershed to yield a total score.

Scores for each deposit type were classified as indicating high, medium, low, or unknown potential, and these results were assigned as an attribute to each subwatershed. Each subwatershed also was assigned a value representing certainty of the modeled potential that reflects the number of datasets that contributed to the score. High certainty indicates that multiple datasets contributed to the score, whereas low certainty indicates that only a few datasets contributed to the score. Detailed tables were published for each deposit type that describe the data layers and criteria used to generate the scoring rubric. The scoring rubric was developed by simultaneously analyzing multiple geoscience data layers using Python scripts in ArcGIS; the scores were weighted and classified according to the importance of a particular parameter to the likelihood of a mineral system being present (Karl and others, 2016; Karl and others, U.S. Geological Survey, written commun., 2020).

For mineral systems that have published prospectivity models, preliminary focus areas were drawn around regions containing subwatersheds that were classified as having high to medium potential. In most cases, the focus areas directly match the areas outlining elevated prospectivity in the published reports (Karl and others, 2016; Karl and others, U.S. Geological Survey, written commun., 2020). For mineral systems that have not been analyzed utilizing the data-driven approach outlined above, other sources of data were used for delineation of the focus areas. In the case of porphyry Cu and climax-type porphyry Mo systems, a review paper (Kreiner and others, in press) focused on porphyry systems in Alaska was used as the primary source. For the iron-oxide copper gold (IOCG) and metamorphic mineral systems, potential IOCG-style and graphite mineral occurrences described in ARDF were combined with queries of key lithologic units in the geological map database. These components were overlain in ArcGIS together with the digital geologic map. Focus areas outlining permissive geological environments and mineral systems were delineated in ArcGIS using the relevant information as a guide.

Preliminary focus areas were then shared with collaborators at the Alaska Division of Geology & Geophysics for feedback, revision, and additional input. A template was utilized to compile relevant information about each of the focus areas and to identify specific needs for new data acquisition (table 3). Table 3 includes the rationale for delineating each focus area, information about current and past production, and the potential for future discovery of critical minerals (Dicken and Hammarstrom, 2020).

Table 3. Focus area template.

[Abbreviations are defined in the Abbreviations and Chemical Symbols lists near the front of the report. –, No existing Alaska prospectivity model is available.]

Topic	Explanation
Name of focus area	Descriptive geographic or geologic name
Region	Alaska, West, Central, East
Subregion	Alaska, Hawaii, Northcentral, Northeast, Northeast and Southeast, Northwest, Rocky Mountains, South Central, Southeast, Southwest
Mineral system	Select from table 1
Deposit type(s)	Select from table 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 that cover the area	Estimate of the percentage 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 deposits; structures that may control mineralization
Deposits	Name deposits within the focus area that have identified resources or past production
Mineral occurrences	Summarize occurrences, if any, from USMIN, ARDF or other database(s)
Geochemical evidence	Stream sediment, rock, soil indications, or associated commodities
Geophysical evidence	Data that may indicate buried intrusions, extensions of known mineralization, 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 (author(s), 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

Mineral Systems

The following sections provide the background data defining the mineral systems considered in this report. Within each section, the rational for the consideration of the systems and the location of the focus areas in Alaska are provided.

Basin Brine Path

Basin brine path mineral systems generally form from the circulation of marine or terrestrial brines through permeable strata to upwelling and discharge sites where an ore deposit may form if appropriate conditions exist. The fluids are principally derived from dissolution of seawater evaporites (halite, gypsum, and others) in the sedimentary sections, resulting in high-salinity basinal brines (Emsbo, 2009; Hofstra and Kreiner, 2020). Fluids are circulated by topographic drivers, ambient geothermal heat in the crust, or magma emplacement. Fluids will typically flow along lithologic contacts that have strong rheological contrast, flow through fault and fracture networks, or circulate in permeable lithologic units. Mineral deposits form in systems where (1) fluids were able to effectively scavenge metals and transport them as metal-chloride complexes along the flowpaths and (2) favorable traps exist to effectively reprecipitate the metals as ore minerals. Traps may be physical (temperature gradients, depressurization) or chemical (mixing of fluids, interaction with sulfide-bearing rocks, or others).

Local geologic controls will influence the style and geochemistry of the mineralizing system. For instance, in a rift basin, fluids may circulate through red beds and bimodal volcanic rocks, leading to Cu-Co(-Ge-Ga-In-Bi)-bearing sediment-hosted deposits (Hitzman and others, 2010). In contrast, systems in foreland basins may have fluids flowing along a basement-carbonate contact, resulting in Pb-Zn-Ag(-Co-Ge-Ga-In-Bi) MVT-style and sedimentary exhalative (e.g., clastic-dominated deposits [Leach and others, 2010]). Other deposit types formed in basin brine path systems include Li-brine deposits, hydrothermal dolomite, barite deposits, and U deposits (Hofstra and Kreiner, 2020).

Basin brine path mineral systems are prospective for numerous critical minerals. Associated phase 2 critical minerals include Li, Sn, Co, PGE, and REE. Other associated critical minerals include Ge, Ga, In, V, U, Re, Sc, barite, and Sr.

In Alaska, the focus areas for basin brine path systems (fig. 2*A*) include regions prospective for sediment-hosted Cu (e.g., Bornite; Hitzman and others, 1986) and shale-hosted Pb-Zn-Ag deposits (e.g., Red Dog; Leach and others, 2010). These focus areas were delineated based on (1) geochemical signatures; (2) the presence of appropriate lithologies in the stratigraphy that would permit formation of basinal brines and provide sources of metals; and (3) known mineral occurrences that show alteration, mineralogy, and geochemical characteristics consistent with basin brine path mineral systems (Karl and others, 2016). Critical mineral potential in these focus areas in Alaska includes Co, PGE, Ge, Ga, and Sn.

Climax-Type Porphyry Molybdenum

Climax-type porphyry molybdenum systems commonly form in post-subduction, extensional tectonic settings. Most known examples are associated with highly evolved, calc-alkaline granite and subvolcanic high-silica rhyolite porphyry (Seedorff and others, 2005) that are commonly emplaced after the peak of magmatic activity (Ludington and Plumlee, 2009).

Globally, climax-type porphyry molybdenum systems are rare; all known examples occur in western North America (Ludington and Plumlee, 2009). Permeability for fluid flow is created by hydrofracturing related to magma emplacement and evolution of the igneous system. Aqueous supercritical fluids are exsolved from small intrusions and cupolas extending upwards from larger crystallizing batholiths. As the magmatic system overpressures, fluids escape vertically upward and precipitate quartz-molybdenite stockwork veins.

Climax-type Mo porphyry systems are associated with highly evolved silica- and fluorine-rich intrusions also known as rare-metal granites (Ludington and Plumlee, 2009). Host rock composition has little to no apparent control on the size, grade, or minerals associated with the systems. Large thermal and chemical gradients form as exsolved fluids interact with the host rocks and (or) mix with meteoric water along flowpaths in the system, resulting in a broad spectrum of mineral deposit types. Common deposit types associated with climax-type porphyry molybdenum systems include pegmatites, greisen, Mo-skarn, polymetallic veins, alunite- and kaolinite-rich lithocaps, and volcanogenic beryllium and uranium (Hofstra and Kreiner, 2020). These deposits are known to contain a wide variety of critical minerals including Al, Nb, Ta, Sn, and W.

Alaska has several regions that are prospective for rare metal granites and associated climax-type porphyry molybdenum systems (fig. 2*B*). Focus areas for this mineral system were delineated using a combination of geochemical data, lithologic descriptions, and ARDF occurrences that highlight belts prospective for Sn-W-Mo(-Ta-In-fluorspar) deposits associated with specialized granites (Karl and others, 2016). Focus areas also were informed by a recent review paper on porphyry deposits in Alaska that describes the tectonic and magmatic evolution of Alaska porphyry belts (Kreiner and others, in press). Critical mineral potential in these focus areas include Sn, W, Nb, Ta, Li, Re, fluorite, As, and Sb.

IOA–IOCG

Mineral systems of the IOA-IOCG family form in a variety of continental tectonic settings, ranging from subduction systems to extensional settings and rift-related environments. Perhaps the most common tectonic settings are extensional settings in arc and rifts (Hitzman and others, 1992). With only a few known exceptions, IOCG systems form in geologically active regions that have compositionally varied, coeval magmatism (Barton, 2014). Host terranes are typically oxidized (magnetite- or hematite-stable), and the majority exhibit evidence for evaporitic deposits (e.g., evaporites, meta-evaporites, and surficial and sedimentary brines; Barton and Johnson, 1996, 2000). Sources of metals, sulfur, and fluids remain the subject of debate. Many observations are compatible with an igneous, but not necessarily magmatic, source (Barton, 2014). Magmatic fluids are capable of transporting Fe and other metals, but mass balance issues arise when attributing observed volumes of Fe-rich metasomatism to magmatic fluids alone. Similarly, magmatic fluids are also not capable of generating the volumes of sodic-calcic alteration observed in the same systems. External sources of fluids are evidenced by the types and volumes of alteration and mineralization and the overall lack of spatial relationships to igneous rocks of particular compositions (Barton, 2014).

The IOCG systems are strongly zoned vertically and laterally, which results in significant heterogeneity in the deposit-scale characteristics and geochemistry (Kreiner and Barton, 2017). These factors influence the distribution and potential for critical minerals in the systems. Additionally, if external fluids are the predominant fluids in the mineralizing system (cf. Barton, 2014; Barton and Johnson, 1996, 2000), then a strong local control by wall-rock geochemistry along

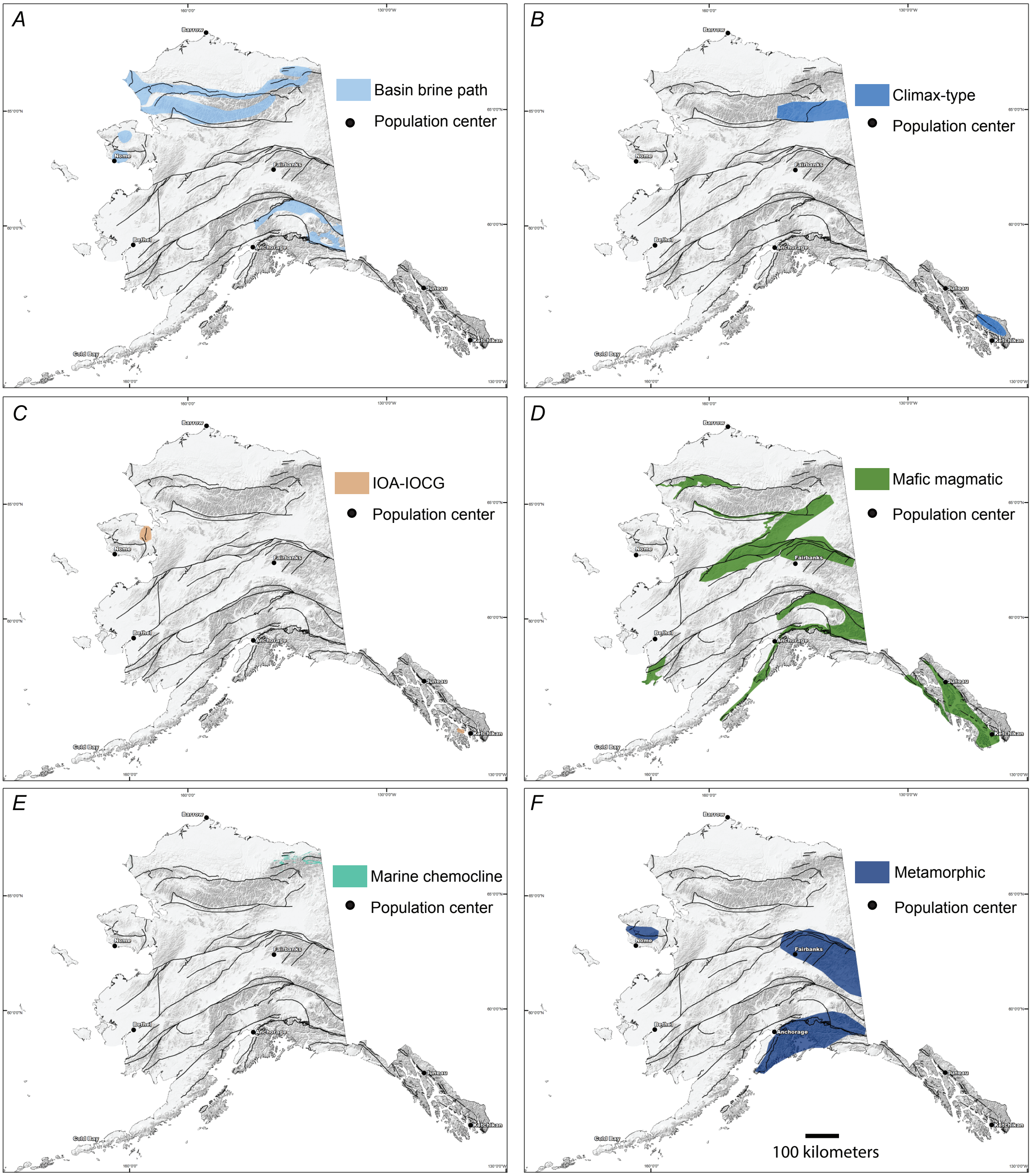

Figure 2. Mineral system focus areas in Alaska. The plates are depicted using the same field of view and base map as figure 1. Abbreviations are defined in the list of abbreviations and list of chemical symbols. *A*, basin brine path mineral system focus areas; *B*, climax-type porphyry molybdenum mineral system focus areas; *C*, IOA-IOCG mineral systems focus areas; *D*, mafic magmatic mineral system focus areas; *E*, marine chemocline mineral system focus areas; *F*, metamorphic mineral system focus areas; *G*, magmatic REE mineral system focus areas; *H*, alkaline porphyry and porphyry Cu-Mo-Au mineral system focus areas; *I*, granite Sn-W mineral system focus areas; *J*, reduced-intrusion related gold and orogenic gold mineral system focus areas; *K*, placer mineral system focus areas; *L*, meteoric recharge system focus areas.

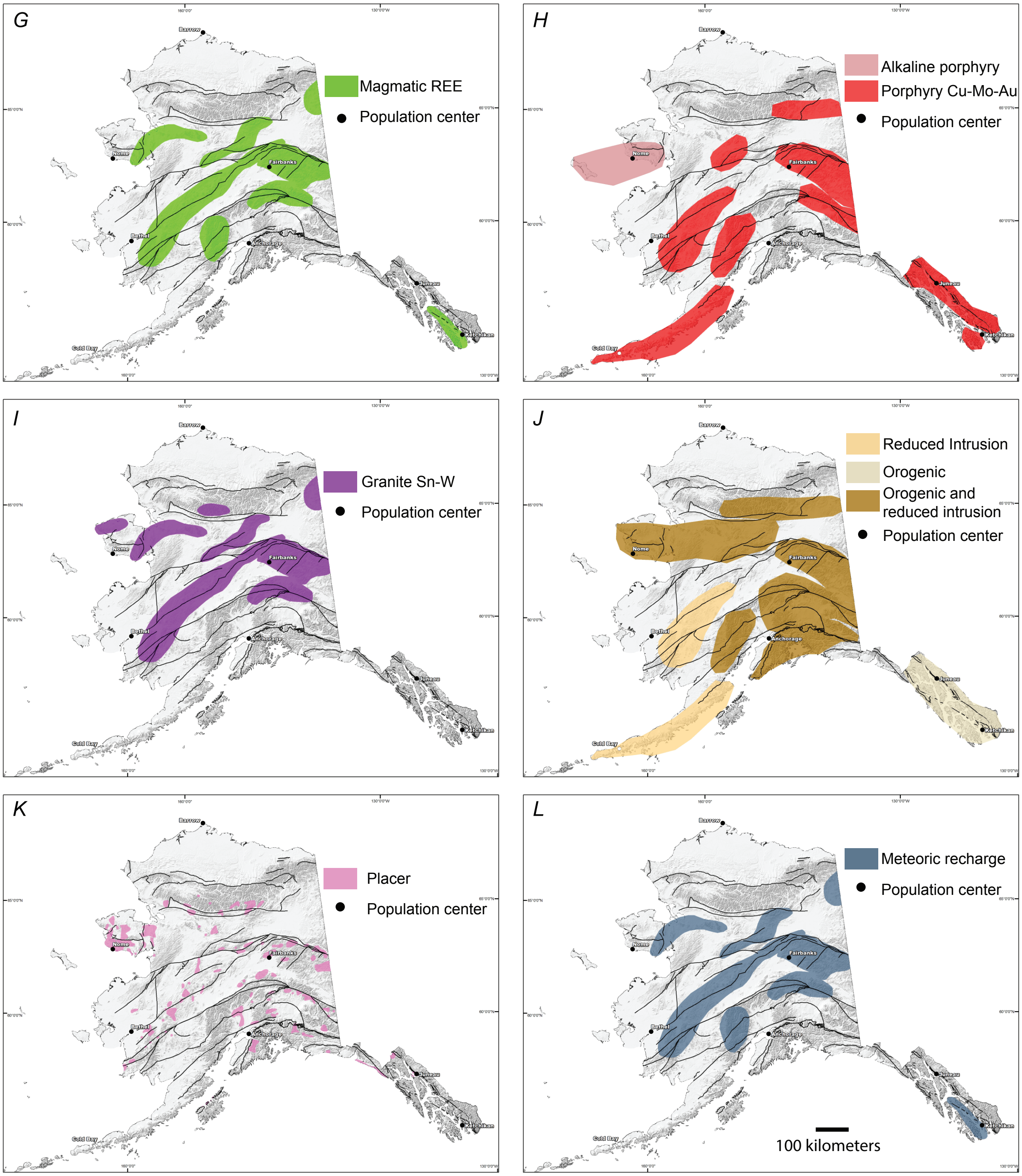

Figure 2.—Continued

the fluid pathways can influence the metals available for scavenging. The IOCG systems may contain a variety of critical minerals including U, REE, Co, As, Mn, and Te (Hofstra and Kreiner, 2020).

In Alaska, only two regions are known to contain mineralized rock that could represent IOCG mineral systems (fig. 2*C*). In all cases, possible IOCG occurrences are poorly documented but do contain an abundance of iron-oxide mineralization together with large volumes of observed Na(-Ca) alteration assemblages that locally include scapolite. As described, these possible Alaska occurrences are not known to contain significant apatite (primary host for REE), but Co may be present.

Mafic Magmatic

Mafic magmatic systems form by partial melting of the mantle that produces basic to ultrabasic mafic and ultramafic intrusions (Cawthorn and others, 2005). Large mafic and ultramafic complexes form in a variety of tectonic settings, leading to a variety of styles that include layered intrusions, unlayered intrusions, zoned ultramafic complexes, and ophiolites. The focus in this report is on zoned ultramafic complexes and ophiolites. Zoned ultramafic intrusions, also referred to as Alaskan-type complexes (Taylor, 1967), occur in orogenic settings and are inferred to represent the subvolcanic roots of arc magmatism. In these environments, water pressure suppresses plagioclase stability, promoting crystallization of hornblende. Ophiolite complexes consist of slices of uppermost mantle and oceanic crust that included ultramafic cumulates, gabbros, and sheeted dikes. In both cases, PGE formation occurs where sulfide droplets form in the magma and scavenge siderophile elements from the melt. Chromium crystallizes from the melt in chromite, which can concentrate into discrete layers in the mafic and ultramafic sequences through density settling processes.

The only known mafic magmatic systems that occur within Alaska are either zoned ultramafic complexes (Alaska-type complexes) or ophiolites (fig. 2*D*). One example of an Alaska-type zoned ultramafic complex is in the Goodnews Bay area of southwestern Alaska (Mertie, 1976). These intrusions are prospective for PGE, Co, Ti, and Cr. Numerous small ophiolite occurrences are scattered throughout the State, but the occurrences have not been the focus of exploration or research to date. Areas that are permissive for these systems were highlighted by the prospectivity model for PGE(-Co-Cr-Cu-Ni-Ti-V) deposits associated with mafic to ultramafic intrusive rocks (Karl and others, 2016). The model focused primarily on the location of geologic environments favorable for mafic and ultramafic rocks and where pathfinder geochemistry highlighted elevated concentrations of key metals.

Marine Chemocline

Marine chemocline mineral systems form in geologic settings where basinal brines are discharged into oceans. This process promotes an increase in biogenic activity and ultimately produces black shales. Changing redox conditions further result in the precipitation of marine phosphorites, marine sedimentary rocks composed of more than approximately 18 percent P_2O_5 (Cathcart, 1980). The key REE-bearing mineral phase that can be precipitated in this environment is a carbonate-rich fluorapatite mineral that is informally named “francolite” (Emsbo and others, 2016). Francolite deposition typically occurs on the margins of sedimentary basins that are aerially extensive over more than 1,000 square kilometers (Emsbo and others, 2016). Emsbo and others (2015) determined that REE enrichment in marine phosphorite units is almost entirely contained in francolite. Further, Emsbo and others (2015) showed that REE concentrations exhibit secular fluctuations globally and that phosphorite beds deposited at certain times globally are much more enriched in REEs than others. Phosphorite beds deposited during the Upper Mississippian, Devonian, Ordovician, and lower Silurian have the highest potential for REE enrichment (Emsbo and others, 2015).

Phosphorite beds are sporadically present across the northern flank of the Brooks Range in Alaska (fig. 2*E*). These phosphorites occur in the Triassic Shublik Formation and the Upper Mississippian Lisburne Group formations. Neither unit has been the focus for REE exploration to date. However, the Lisburne Group contains estimated mean REEs in francolite of 790 ppm ΣHREE (Emsbo and others, 2015).

Metamorphic

Metamorphic mineral systems form in regions undergoing contact or regional metamorphism of organic-carbonaceous rocks or rocks enriched in REE phosphates. Metamorphic processes can recrystallize minerals and concentrate elements into ore-grade seams, pods, and veins. In some cases, these concentrations may be hosted in faults. Vein deposits are often considered to be hydrothermal, but the fluids are metamorphic in origin and derived from devolatization of carbonaceous or calcareous sedimentary rocks during granulite facies metamorphism in the lower crust. These reactions result in C–O–H-rich fluids (Luque and others, 2014; Simandl and others, 2015; Zhong and others, 2019).

Alaska contains one of the largest known flake graphite deposits in the United States at Graphite Creek (Eccles and Nicholls, 2014). In addition to this deposit, graphitic shale and carbonaceous schist are documented in many different geologic belts in Alaska (fig. 2*F*), and some of these belts also expose relatively high-grade metamorphic rocks. Thus, there is potential for undiscovered graphite deposits in the State. Focus areas for metamorphic mineral systems in Alaska were delineated for graphite deposits only, and focus areas are based on known ARDF mineral occurrences and the presence of graphitic rocks in terranes that exhibit characteristics consistent with metamorphic processes.

Magmatic Rare Earth Elements

Systems of the magmatic REE classification are in multiple tectonic settings, but REE classifications predominantly occur in late orogenic or intraplate extensional settings (Cerný and others, 2015). The origin of carbonatites is still debated, although the preponderance of evidence suggests carbonatites are derived from mantle melts (Verplanck and others, 2016). The controversy surrounds the composition of the initial melts and how magmas evolve to form the carbonatite mineralogy. Peralkaline granites represent the products of extensive fractional crystallization, which is in part related to the high halogen and alkali contents of the parent magmas (Dostal, 2016). In carbonatite and peralkaline magmatic systems, REE mineralization occurs during the latest stages of magma evolution when REE-bearing minerals finally crystallize. Locally, hydrothermal fluids exsolved during the waning stages of crystallization may remobilize and enrich the original magmatic ore assemblages (Dostal, 2016).

Globally, magmatic REE mineral systems are prospective for phase 2 critical minerals including REE, Nb, and Ta (Hofstra and Kreiner, 2020). Other critical minerals known to occur in these systems include Y, Zr, Hf, Be, U, Th, P, Sr, and Ba (Hofstra and Kreiner, 2020).

Alaska contains carbonatite occurrences and peralkaline igneous systems that have potential for REE mineralization (fig. 2*G*). Bokan Mountain in southeastern Alaska is a source of HREEs associated with a peralkaline intrusive complex and dike swarm (Bentzen and others, 2013; Dostal and others, 2013, 2014). Tofty is an occurrence in eastern interior Alaska that is interpreted to be a carbonatite complex (Warner and others, 1986; Verplanck and others, 2014). Focus areas for magmatic REE systems in Alaska were identified on the basis of the data-driven, GIS prospectivity analyses that used criteria including alkaline-peralkaline igneous geochemical compositions, anomalous pathfinder and REE geochemistry in stream sediments, and known mineral occurrences throughout the State (Karl and others, 2016).

Porphyry Cu-Mo-Au and Alkaline Porphyry

Porphyry Cu-Mo-Au systems form in magmatic arcs above active subduction zones at convergent plate margins (Richards, 2003; Seedorff and others, 2005). Formation of porphyry systems begins with the construction of an intermediate silica-saturated magma chamber. The process is generally initiated with the generation of mantle-sourced melts aided by fluids derived from dehydration reactions in the subduction zone. Mafic magmas rise into the crust and hybridize with crustal partial melts, leading to fractional crystallization (Hildreth, 1981). Generally, porphyry systems form in the later stage of magmatic processes and evolution. Formation of a porphyry deposit requires volatile exsolution to produce a separate aqueous phase, which then must adequately scavenge metals from a sufficient volume of the silicate melt and any preexisting magmatic sulfides. Fluids and complexed metals then gather in the cupola of a crystallizing pluton where overpressure and hydrofracturing allow the fluids to rapidly ascend to the site of deposition (e.g., Candela and Piccoli, 2005).

Magma composition affects the available metals and metal ratios that may be present in porphyry systems. The diversity of geochemical characteristics in deposits is caused principally by the initial magmatic composition, hydrologic factors (including depth of emplacement, hydrofracturing patterns, and permeability of host rocks), wall-rock composition and the degree of interaction of magmatic fluids with the wall rock (fluid:rock ratio), and the potential interaction of the primary magmatic fluids with secondary external fluids (Seedorff and others, 2005).

Alkalic porphyry systems form through similar geologic processes in continental margin and island arc magmatic belts. Causative intrusions are more fractionated and alkaline in composition, and corresponding alteration is typically enriched in potassic assemblages. Resulting deposits may be more enriched in Au or Mo.

The porphyry mineral system has a variety of deposit styles that reflect ore mineral deposition at different points along the geochemical path of an evolving system. The different deposit types that may be present in the system include disseminated, bulk tonnage, classic porphyry system, base metal skarns, polymetallic veins (including Cordilleran-style), epithermal style mineralization (high-sulfidation veins), and lithocaps enriched in alunite and kaolinite (Hofstra and Kreiner, 2020). Porphyry mineral systems are prospective for phase 2 critical minerals W, PGE, Co, and Al. Additional critical minerals known to occur in porphyry systems include Sn, Bi, Re, Te, Bi, Ge, Ga, In, Sb, As, and Mn.

In Alaska, known deposits exhibit characteristics of the porphyry, skarn, high sulfidation epithermal, and polymetallic vein styles of the porphyry Cu-Mo-Au system. The Pebble deposit in south-central Alaska is one of the world's largest known porphyry Cu-Mo-Au systems (Kelley and others, 2013). In addition to Pebble, numerous porphyry occurrences have been documented in the western Alaska Range and on the Alaska Peninsula (fig. 2*H*). Other porphyry occurrences are documented throughout the eastern Alaska Range and in portions of interior Alaska, northwest Alaska, and southeast Alaska (fig. 2*H*; Kreiner and others, in press). One belt of alkaline-related porphyry systems has been identified on St. Lawrence Island and Seward Peninsula where porphyry Mo systems are associated with syenite intrusions (fig. 2*H*). Focus areas were selected based on a recent review of the tectonic and magmatic controls on porphyry systems in Alaska

(Kreiner and others, in press). The review documents the belts containing known porphyry occurrences or regions that contain favorable tectonic and magmatic settings and may host deposits of the porphyry Cu-Mo-Au mineral system.

Granite Sn-W

Porphyry Sn-W mineral systems include deposits such as porphyry Sn and porphyry W-Mo. Porphyry Sn deposits are only known to occur in Bolivia, except for one potential occurrence at Majuba Hill in Nevada (Seedorff and others, 2005). Porphyry W-Mo deposits are relatively rare and have significant overlap and similarities to porphyry Mo deposits, yet contain much higher W (Seedorff and others, 2005). In addition, porphyry W-Mo deposits have mineral assemblages indicating substantially lower oxidation and sulfidation state than porphyry Mo systems. Porphyry W-Mo deposits form in similar tectonic settings as the porphyry Mo systems, which include magmatic arcs, postsubduction settings, and extensional tectonic settings. As is the case with the porphyry Cu-Mo-Au systems discussed above, porphyry Sn-W and porphyry W-Mo deposits form through magmatic processes related to subduction.

This mineral system also includes greisens and pegmatites that commonly occur in association with highly fractionated silicic, or "specialized granites" (Cerný and others, 2015). Specialized granites form in back-arc settings together with peraluminous granites. Other deposit types include lithocaps and high-sulfidation systems that are associated with porphyry Sn deposits but are largely absent in porphyry W systems. Porphyry Sn-W mineral systems are prospective for phase 2 critical minerals such as Sn, W, Li, Nb, Ta, and Al. Additional critical minerals also include Cs, Be, Nb, Ge, Ga, In, Bi, Sb, and As.

In Alaska, there are no known porphyry Sn occurrences, but documented Sn occurrences show greisen-style mineralization that seems to be related to specialized granites (fig. 2*I*). These occurrences are localized in northwest Alaska on the Seward Peninsula (Karl and others, 2016). Porphyry W-Mo occurrences are scattered across the State, but the occurrences seem to be particularly abundant in the eastern interior (fig. 2*I*; Kreiner and others, in press). Focus areas in Alaska were delineated on the basis of the data-driven prospectivity analysis for Sn-W-Mo(-Ta-In-fluorspar) deposits associated with specialized granites. This prospectivity analysis relied on igneous rock classification and pathfinder geochemistry in bedrock and stream sediment samples (Karl and others, 2016). Additionally, the porphyry Mo-W focus areas were developed using Kreiner and others (in press) as a guide.

Reduced Intrusion-Related Gold and Orogenic

Reduced intrusion-related and orogenic gold mineral systems are grouped together in this report because these systems are derived from the same data-driven prospectivity model in Alaska (Karl and others, U.S. Geological Survey, written commun., 2020). These mineral systems were treated as a single model because of significant overlap in geologic environments and geochemical signatures. To differentiate between these deposit types in the field is difficult for many researchers; for example, Pogo has been referred to as intrusion-related gold (Lang and Baker, 2001) and orogenic (Goldfarb and others, 2000).

Orogenic gold systems form in low-grade metamorphic rocks during the late stages of collisional orogenic events. Orogenic systems may be hosted in accreted terranes, arc and back arc settings, and craton margin settings (Goldfarb and others, 2001). Mineralized systems are hosted in deformed and variably metamorphosed rock units typically at greenschist facies. However, orebodies of economic size may be present in higher- and lower-grade metamorphic host rocks. Fluids in orogenic systems are thought to be derived from devolatilization reactions during metamorphism and are often C–O–H-dominant.

Devolatilized, carbonaceous metasedimentary and metavolcanic rocks in the host belt and (or) the subducting slab, are hypothesized as possible gold sources in some orogenic deposits (Pitcairn and others, 2006; Tomkins, 2013; Goldfarb and Groves, 2015). Debate remains concerning the source of the gold in some Alaska deposits. Most orogenic deposits do not seem to have a strong spatial or temporal association with intrusions; therefore, a link between orogenic veins and coeval magmatism has not been directly established (Groves and others, 2016).

Reduced intrusion-related gold systems form predominantly in regions where crustal thickening occurred (Goldfarb and others, 2000; Lang and Baker, 2001). However, mineral systems may form in a variety of tectonic settings including back arc, foreland fold and thrust, collisional, post-collision, and within active magmatic arcs (Lang and Baker, 2001). In all cases, the prerequisite is the ability to generate melts that form I-type intrusions that have reduced (ilmenite much greater than magnetite) subalkalic and metaluminous character (Thompson and others, 1999). Mineralization in the deposits is strongly spatially correlated with more fractionated phases occurring late in the magmatic evolution. Fluids tend to be carbon-dioxide enriched in the early hydrothermal stages evolving to aqueous brines with time and at shallower levels.

Tungsten is the only phase 2 critical mineral known to occur in association with orogenic and reduced-intrusion-related mineral systems (Hofstra and Kreiner, 2020). Tungsten may be associated with the primary Au mineralization in these systems or may form adjacent W-dominant skarn deposits. Additional critical minerals that occur in these systems include Bi, Te, As, and Sb. Some orogenic systems also may be linked with the formation of graphite deposits.

In Alaska, many of the belts known to contain orogenic and intrusion-related gold mineral occurrences and deposits overlap in space (fig. 2*J*). Many of these belts include areas underlain by extensive metasedimentary rocks (Seward Peninsula, southeastern Brooks Range, and east-central

Alaska) and mixed metavolcanic and metasedimentary rocks (Yukon-Tanana Upland, Juneau gold belt, and southern Prince of Wales Island in southeastern Alaska), which also have been intruded by nominally reduced, subalkalic, and metaluminous plutons (fig. 2*J*). Southeast Alaska, on the other hand, contains no known prospectivity for intrusion-related gold but hosts a number of orogenic gold systems (e.g., the Kensington Mine, Miller and others, 1995; and the Juneau gold belt, Miller and others, 2000; fig. 2*J*). In southwestern Alaska, belts in the Kuskokwim Mountains and the Alaska Peninsula (fig. 1) host multiple intrusion-related gold systems but do not exhibit prospectivity for orogenic gold systems (fig. 2*J*).

Placer

Placer systems form through mechanical erosion processes where minerals of high density are removed from host rocks and concentrated through gravity separation. Heavy minerals are separated from primary host rocks through weathering and erosion before being transported in fluvial and marine systems and deposited in surficial deposits. Fluvial placer deposits form in alluvial drainage networks and mimic the composition of the host rocks occurring within the drainage basin. Heavy minerals that occur within the host rocks are represented by the deposits that form in places where stream gradients change abruptly. These locations may be under large boulders, inside meander bends, in pools that occur below falls and rapids, or in slackwater or eddies. Larger grains tend to concentrate at the gravel-bedrock interface, particularly within existing bedrock fractures or irregular surfaces on the underlying surface. In older landscapes, rivers may incise through older surfaces in response to uplift, leaving higher terraces that can remain prospective for placer deposits and (or) redistributing previously concentrated heavy minerals farther downstream. Marine placers form in a variety of settings that are dominated by eolian, wave, and tidal processes. Heavy minerals in this environment are introduced by rivers that have transported heavy minerals from inland regions and (or) by erosion of bedrock exposures that occur locally. Longshore currents and varying wave patterns may locally redistribute and reconcentrate the heavy minerals in coastal environments.

Placer deposits are perhaps best known for containing gold, but the deposits also may be resources for phase 2 critical minerals such as REE, Nb, PGE, Sn, W, Ta, and Ti. In some cases, placer deposits also may be prospective for U, barite, fluorite, Mn, Zr, and Hf.

Placer gold deposits led to the initial settlement of Alaska and continue to contribute to the mining industry's economic impact on the State (Athey and Werdon, 2019). Placers are known to occur in all geologic environments across Alaska (Nokleberg and others, 1987; fig. 2*K*). Perhaps the most significant are explored for gold, but some are known to contain resources of PGEs (Goodnews Bay in southwest Alaska; Mardock and Barker, 1991), and others contain REE, Sn, W, Ag, Hg, and Ti (Chapman and others, 1963; Nokleberg and others, 1987). The local geochemistry of the placers closely reflects the geochemistry of the host rocks. Placer focus areas in Alaska were delineated from the data-driven prospectivity model that used the following key criteria: the presence of known mineral occurrences, heavy-mineral concentrate mineralogy from panned concentrates, stream-sediment geochemistry, lithologic composition, and mapped river or stream reaches that show appropriate alluvial systematics (Karl and others, 2016).

Meteoric Recharge

Meteoric recharge systems commonly form in sandstone ranging in age from Carboniferous to Holocene. Oxidized meteoric groundwater descends through sandstone aquifers and scavenges uranium and other elements from detrital minerals and (or) volcanic glass through dissolution. Ore metals are transported in solution until an appropriate trap is encountered. Deposits may be basal, tabular, roll front, or tectonolithologic in form (Cuney and Kyser, 2009). In all cases, U is precipitated at the redox front where the oxidized ore fluid interacts with a reduced component (Cuney and Kyser, 2009; Bruneton and Cuney, 2016; Hall and others, 2019). Reducing components may be other meteoric fluids or reduced host rocks.

Meteoric systems may contain a wide array of trace and critical elements, dependent on the initial basinal characteristics and compositions of the source rocks. Phase 2 critical minerals include REE, Co, and PGE. Additional critical elements include U, Cr, V, Re, Se, Sr, and Sc. Additional metals also include Cu, Fe, Mo, Pb, Zn, Ag, and Cd.

In Alaska, the most prospective region includes the Death Valley prospect (Karl and others, 2016) on the Seward Peninsula (fig. 2*L*). Additional areas were highlighted by the prospectivity analysis based on the presence of appropriate sandstone host rocks, geochemistry, and mineral occurrence data (Karl and others, 2016; fig. 2*L*). Many focus areas coincide with the presence of Tertiary arkosic sandstones and (or) coal-bearing units—signifying many key ingredients present for the development of sandstone-hosted U deposits such as Death Valley (Karl and others, 2016).

Discussion

Alaska Earth MRI focus areas described in this report (fig. 2*A–L*) highlight areas that may be prospective for phase 2 critical minerals but that also require new data acquisition and research. Some of the focus areas have historical production, currently produce, or have identified resources known to contain critical minerals. Many focus areas contain the necessary geological ingredients for a mineral system known to be prospective for critical minerals. Most Alaska focus areas were delineated using published, data-driven geospatial analyses that utilized publicly available statewide datasets. Others were defined on the basis of prospective geologic characteristics that are consistent with mineral systems described above. Focus areas are necessarily broad, which reflects significant gaps in modern data coverage and quality across a large, remote, and geologically complex State.

This report defines 74 Alaska Earth MRI phase 2 focus areas, which are listed in Dicken and Hammarstrom (2020). These focus areas span large regions of the State and occur in multiple, diverse geological belts. To help prioritize new geological, geophysical, and geochemical data collection in the State, the authors mapped out the number of phase 2 focus areas that occur within each 1:63,000 quadrangle in the State. In figure 3, each 1:63,000 scale quadrangle that contains at least one focus area is shown. Those quadrangles containing more than one focus area are shown in increasingly warm colors (see explanation) to a maximum of 12 (fig. 3). The resulting data (table 4) indicate that 2,023 (approximately 67 percent) of the 3,011, 1:63,360-scale quadrangles in the State contain at least one focus area delineated in this report. More than 300 quadrangles have 6 or more overlapping focus areas. Areas of the State that have the most overlap of mineral systems containing critical minerals are expected to have the highest potential for producing new discoveries. Prioritizing new data collection in these regions will be most efficient and effective for developing a more complete and modern understanding of the deposit types and styles that are present and how associated critical minerals are mobilized and concentrated in a variety of geologic environments.

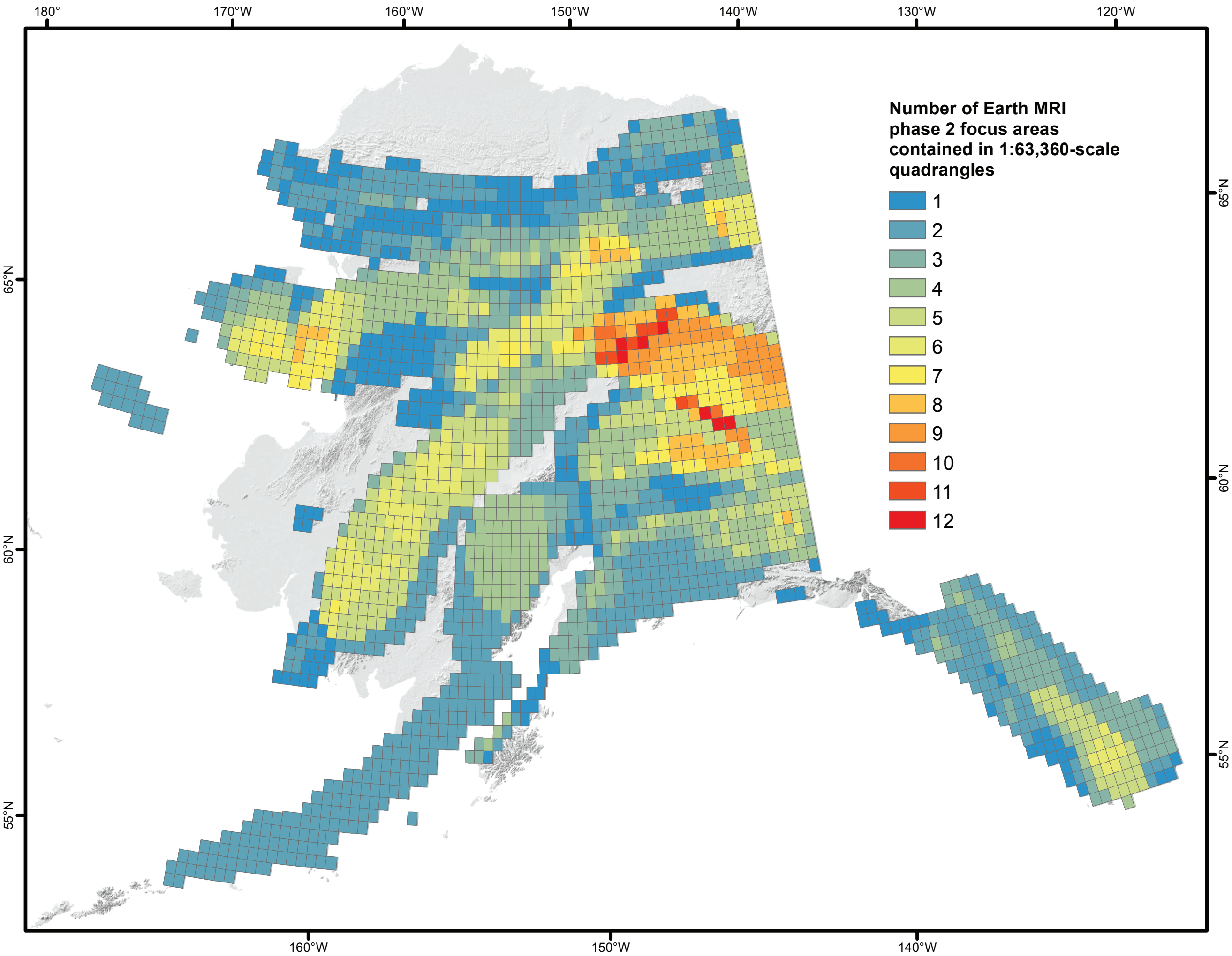

Figure 3. Overlap of mineral system focus areas showing the Alaska 1:63,360-scale quadrangles containing one or more phase 2 Earth MRI focus areas. Colors correspond to the number of focus areas the quadrangles contain; values range from 1 (blue) to 12 (red).

Table 4. Alaska 1:63,360 quadrangles containing one or more Earth Mapping Resources Initiative (Earth MRI) phase 2 focus areas.

Number of focus areas	Alaska 1:63,360 quadrangles containing all or part of the number of focus areas to left
1	286
2	597
3	280
4	291
5	237
6	141
7	67
8	65
9	40
10	4
11	8
12	7

Summary

Alaska focus areas for phase 2 of the Earth MRI have been defined based on a data-driven, mineral systems approach that uses publicly available statewide datasets to map prospectivity for a variety of mineral deposit groups. The prospectivity maps and associated data highlight regions that are prospective for mineral systems that may contain critical minerals of current interest. In addition, the statewide prospectivity analyses identify key gaps in existing datasets that highlight the need for new data collection throughout Alaska. Prioritization of data acquisition through the Earth MRI program is informed by the data gaps highlighted in the prospectivity analyses.

Earth MRI phase 2 critical minerals have been identified in 12 mineral systems in Alaska. A total of 74 focus areas were developed to encompass the regions that are favorable for mineral systems that may contain the critical minerals. Evaluating the amount of spatial overlap at the quadrangle scale provides a useful tool for prioritizing new Earth MRI geologic, geophysical, and geochemical data acquisition into regions that exhibit the greatest variety of prospective mineral systems.

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