Systems-Deposits-Commodities-Critical Minerals Table for the Earth Mapping Resources Initiative

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Conversion Factors

International System of Units to U.S. customary units

| Multiply | By    | To obtain         |
|----------|-------|-------------------|
|          | Length|                   |
| kilometer (km) | 0.6214 | mile (mi)         |
|          | Area  |                   |
| square kilometer (km²) | 0.3861 | square mile (mi²) |

Abbreviations

Earth MRI  Earth Mapping Resources Initiative
PGE     platinum group elements
REE     rare earth elements
USGS    U.S. Geological Survey
## Chemical Symbols

| Symbol | Element       |
|--------|---------------|
| Ag     | silver        |
| Al     | aluminum      |
| Ag     | silver        |
| Al     | aluminum      |
| As     | arsenic       |
| Au     | gold          |
| BaSO₄  | barite        |
| Be     | beryllium     |
| Bi     | bismuth       |
| C      | graphite       |
| CaF₂   | fluorspar     |
| Co     | cobalt        |
| Cr     | chromium      |
| Cs     | cesium        |
| Cu     | copper        |
| Fe     | iron          |
| Ga     | gallium       |
| Ge     | germanium     |
| He     | helium        |
| Hf     | hafnium       |
| In     | indium        |
| KCl    | potash        |
| Li     | lithium       |
| Mg     | magnesium     |
| Mn     | manganese     |
| Mo     | molybdenum    |
| Nb     | niobium       |
| Ni     | nickel        |
| P      | phosphorus    |
| Pb     | lead          |
| Rb     | rubidium      |
| Re     | rhenium       |
| Sb     | antimony      |
| Sc     | scandium      |
| Element | Symbol | Element   | Symbol | Element   | Symbol | Element   | Symbol |
|---------|--------|-----------|--------|-----------|--------|-----------|--------|
| Sn      | tin    | Sr        | strontium | Ta       | tantalum | Te        | tellurium |
| Ti      | titanium | U         | uranium | V        | vanadium | W         | tungsten |
| Zn      | zinc   | Zr        | zirconium |
Systems-Deposits-Commodities-Critical Minerals Table for the Earth Mapping Resources Initiative

By Albert H. Hofstra and Douglas C. Kreiner

Abstract

To define and prioritize focus areas across the United States with resource potential for 35 critical minerals in a few years’ time, the U.S Geological Survey Earth Mapping Resources Initiative (Earth MRI) required an efficient approach to streamline workflow. A mineral systems approach based on current understanding of how ore deposits that contain critical minerals form and relate to broader geologic frameworks and the tectonic history of the Earth was used to satisfy this Earth MRI need. This report describes the rationale for, and structure of, a table developed for Earth MRI that relates critical minerals and principal commodities to the deposit types and mineral systems in which they are concentrated. The hierarchical relationship between systems, deposits, commodities, and critical minerals makes it possible to define and prioritize each system-based focus area once for all of the critical minerals that it may contain. This approach is advantageous because mineral systems are much larger than individual ore deposits and they generally have geologic features that can be “imaged” by the topographic, geologic, geochemical, and geophysical mapping techniques deployed by Earth MRI.

Background

The President and Secretary of the Interior issued orders (Executive Office of the President, 2017; U.S. Department of the Interior, 2017) that directed the U.S. Geological Survey (USGS) to develop a plan to improve the Nation’s understanding of domestic critical mineral resources. In response, a list of 35 critical minerals with a high risk for supply disruption were identified by the National Minerals Information Center (Fortier and others, 2018). The 35 critical minerals that were identified are aluminum (Al), antimony (Sb), arsenic (As), barite (BaSO₄), beryllium (Be), bismuth (Bi), cesium (Cs), chromium (Cr), cobalt (Co), fluor spar (CaF₂), gallium (Ga), germanium (Ge), graphite (C), hafnium (Hf), helium (He), indium (In), lithium (Li), magnesium (Mg), manganese (Mn), niobium (Nb), platinum group elements (PGEs), potash (KCl), rare earth elements (REE), rhenium (Re), rubidium (Rb), scandium (Sc), strontium (Sr), tantalum (Ta), tellurium (Te), tin (Sn), titanium (Ti), tungsten (W), uranium (U), vanadium (V), and zirconium (Zr).

In 2018, Congress allocated funds to the USGS Mineral Resources Program for the Earth Mapping Resources Initiative (Earth MRI), which is a partnership between the USGS, the Association of American State Geologists, and other Federal, State, and private-sector organizations. The goal of Earth MRI is to generate maps and data that aid in increasing the domestic inventory of critical minerals (Day, 2019). To reach this goal, focus areas with critical mineral resource potential must be defined and prioritized for new topographic, geologic, geochemical, and geophysical mapping; and funds must be allocated to States and contractors to conduct the work. The new maps of high priority focus areas are designed to (1) advance understanding of, or “image,” the three-dimensional geologic framework, (2) stimulate exploration and development of domestic resources of critical minerals, and (3) decrease the Nation’s reliance on foreign sources of critical minerals.

During Phase 1, focus areas with potential for REE-bearing deposit types were targeted and classified by geologic environment (Dicken and others, 2019; Hammarstrom and Dicken, 2019). In 2019, funds were allocated to map the prioritized REE-focus areas and several studies were underway in 2020. During Phase 2, focus areas with potential for Al, C, Co, Li, Nb, PGE, Sn, Ta, Ti, and W were targeted and classified into mineral systems (explained in the “Mineral Systems” section) that generate ore deposits containing the aforementioned critical minerals. The plan for Phase 3 is to target and classify all or most of the remaining critical minerals (As, BaSO₄, Be, Bi, CaF₂, Cr, Cs, Ga, Ge, He, Hf, In, KCl, Mg, Mn, Re, Rb, Sb, Sc, Sr, Te, U, V, and Zr).

Problem and Solution

To define and prioritize Earth MRI focus areas across the United States for 35 critical minerals in a few years’ time, an efficient method was needed that minimized the number of focus areas and the number of times that each focus area was considered. Application of the commodity-based approach utilized for REE in Phase 1 to the remaining 34 critical minerals would be redundant and inefficient because, unlike REE and
a few other exceptions (Al, BaSO₄, C, PGE), critical minerals generally do not constitute the major part of any single mineral deposit. Instead, they are more commonly present as minor constituents in deposits mined for principal commodities, such as gold (Au), silver (Ag), lead (Pb), zinc (Zn), copper (Cu), molybdenum (Mo), nickel (Ni), iron (Fe), and phosphorus (P).

The solution to this problem, employed in Phases 2 and 3 of Earth MRI, was to take advantage of the hierarchical relationship that exists between mineral systems, ore deposits, principal commodities, and critical minerals (described in the “Table Rationale and Explanation” section) and define focus areas that correspond, more or less, to the footprint of mineral systems, and then prioritize each system-based focus area once for the entire suite of critical minerals that it may contain. An important advantage of this approach is that the scale of mineral systems is much larger than individual ore deposits and they generally have key geologic features that can be “imaged” by the Earth MRI mapping techniques described previously. The number of focus areas can be further reduced by prioritizing only the largest and most prospective systems in the United States because, in most (but not all) cases, small systems are unlikely to generate deposits that are large enough to contain significant quantities of critical minerals. Another way to minimize the number of focus areas is to group mineral systems that occur in clusters or belts into one focus area. Similarly, because well-endowed mineral systems are known to form in specific tectonic settings and during specific time periods of Earth history, such settings that have been identified in frontier areas or under cover can be designated as focus areas.

In the following sections, we describe mineral systems and the rationale for, and structure of, the systems, deposits, commodities, and critical minerals information compiled in table 1 (PDF file) and show how it can be used to streamline workflow for Earth MRI.

Mineral Systems

The mineral systems concept is based on current understanding of how ore deposits form and relate to broader geologic frameworks and the tectonic history of the Earth (for example, Wyborn and others, 1994; McCuaig and others, 2010; Huston and others, 2016; and Geological Survey of Western Australia, 2019). Mineral systems encompass all of the components required to form ore deposits (fig. 1). These components are (1) an optimum geotectonic setting, (2) energy to drive the system (heat, gravity), (3) source rocks for ligands and metals (igneous, metamorphic, or sedimentary rocks; preexisting mineralization), (4) a transport medium (melts, aqueous fluids-liquids-vapors, petroleum-natural gas), (5) transport pathways (channels, permeable structures and lithologies), (6) chemical and physical traps that concentrate metals to ore grades (deposits), and (7) distal expressions (mineral, chemical, or thermal anomalies) that extend to the limit of the system. In a given geotectonic setting, variations in these components, produce mineral systems and ore deposits of different types that are enriched in different principal commodities and byproducts, of which some are critical minerals.

Mineral systems with genetically related ore deposits generally form during an episode of magmatism, metamorphism, deformation, sedimentation, weathering, or erosion in specific geotectonic settings (fig. 1). The geotectonic setting includes the actual tectonic configuration as well as aspects of crustal evolution and (or) climatic conditions that are required for a system to produce significant deposits. If a setting lacks one or more key ingredients, such as dilatant structures, enriched source rocks, an arid climate, or appropriate physical or chemical conditions, a mineral system may operate without producing significant ore deposits. Systems generally require a trigger to get them started. Triggers can be sudden, such as volcanism above a mantle plume (for example, Ni-Cu-PGE deposits in a mafic magmatic system), or barely noticeable, such as formation of a peneplain in a tropical climatic zone (for example, bauxite deposits in a chemical weathering system).

The vertical and lateral extents of mineral systems are quite variable. For example, a system may have large vertical extents, as in porphyry Cu-Mo-Au systems that extend from the subduction zone to the surface (fig. 2C), or short vertical extents, such as chemical weathering systems that are restricted to the vadose zone between the surface and the water table. Mineral systems can have large lateral extents, as in basin brine path systems that extend from marine evaporite basins, across passive margins, to shelf-slope breaks where they discharge into the ocean (fig. 3). Other mineral systems can have small lateral extents, such as in carbonatites. Most systems are spatially zoned such that deposits with different commodities and critical minerals occur at different levels or in proximal to distal positions (for example, figs. 2A and 3). In some systems, critical minerals are enriched on the periphery of the system or deposit types within it, or they occur in unconventional deposit types (for example, alunite altered lithocaps). Some deposit types are mined for a single commodity, such as tungsten skarn deposits, whereas others are mined for several commodities, such as placer deposits mined for Au, REE, Ti, and Zr-Hf. In some deposit types, the principal commodity is a critical mineral, but in most cases critical minerals have been, or may only be, produced as byproducts of principal commodity deposits (Hayes and McCullough, 2018), such as REE from sedimentary phosphate deposits.

Detailed information on each system and deposit type is provided in the references cited in table 1.

Table Rationale and Explanation

Table 1 was populated with principal commodity and critical mineral information gathered from ore deposit models published by the USGS, other government organizations, and scientific journals. This information was classified into mineral systems using the concept outlined in the “Mineral Systems” section. This classification consisted of grouping deposit types
Figure 1. Mineral system concepts. A, Modified from Knox-Robinson and Wyborn (1997). B, Modified from Geoscience Australia (2019). (∅, less than or equal; km, kilometer)
Figure 2. Schematic cross sections of a porphyry copper (Cu)-molybdenum (Mo)-gold (Au) system (with critical minerals in blue) at various scales. A and B, Modified from Sillitoe (2010). C, Modified from Tosdal and others (2009). (Ag, silver; Al, aluminum; As, arsenic; Be, beryllium; Bi, bismuth; Co, cobalt; dissem., disseminated; Ga, gallium; Hg, mercury; In, indium; K, potassium; km, kilometer; Li, lithium; MASH, melting, assimilation, and homogenization; Mn, manganese; Pb, lead; PGE, platinum group elements; Re, rhenium; Sb, antimony; SLM, subcontinental lithospheric mantle; Sn, tin; Te, tellurium; W, tungsten; Zn, zinc)
Figure 3. Schematic model of a basin brine path system (with critical minerals in blue), modified from Emsbo, 2009. (> , greater than; %, percent; Ba, barium; Bi, bismuth; Co, cobalt; Cs, cesium; Cu, copper; Fe, iron; Ga, gallium; Ge, germanium; In, indium; K, potassium; km, kilometer; km², square kilometer; Li, lithium; Mg, magnesium; Mn, manganese; MVT, Mississippi Valley-type; Na, sodium; Pb, lead; PGE, platinum group elements; PO₄, phosphate; Rb, rubidium; Re, rhenium; REE, rare earth elements; U, uranium; V, vanadium; Sb, antimony; Sr, strontium; TOC, total organic carbon; Zn, zinc)
that share a fundamental genetic relationship to geologic controls that are characteristic of each system type. Thus, if one part (for example, deposit type) of a system is identified, then the other parts (for example, other deposit types) of the system may be present nearby.

As table 1 was being constructed, it became clear that it could be simplified and made more useful for Earth MRI by (1) grouping deposit types with similar mineral assemblages that contain similar element suites, and (or) (2) splitting out deposit types with distinct mineralogies and elements. This decision was based on the common mineral associations that occur in certain deposit types and the typical element substitutions that occur in each mineral. For example, in porphyry Cu-Mo-Au systems (fig. 2A–B), polymetallic skarn, replacement, vein, and intermediate sulfidation (SRVIS) deposits all contain various proportions of Cu-, Zn-, and Pb-sulfides and As- and Sb-sulfosalts with variable proportions of the same principal commodities (Cu, Zn, Pb, Ag, Au) and critical minerals (Ge, Ga, In, Bi, Sb, As, W, Te). Thus, an overarching deposit name was devised to encompass them, “polymetallic SRVIS.” In an analogous way, Cu-sulfides in porphyry and skarn copper deposits typically contain PGE, Te, and Bi; molybdenite in porphyry and skarn molybdenum deposits contains Re; pyrite in distal disseminated silver-gold deposits contains As and Sb; and alunite in lithocap deposits contains Al, K, and Ga. Placers are more complex because the assemblage of ore minerals that they contain reflects the assemblage of source rocks and mineralization exposed in the catchment area. Consequently, it is important to understand that the distinctions made in table 1 are idealized and that in nature the deposit types grade into, or overlap with, one another. Nevertheless, the deposit groupings and distinctions can be used to identify the parts or aspects of a mineral system that are likely to be enriched in specific principal commodities and critical minerals.

### Table Structure

The table consists of six columns (with headers in bold type). The first is the “System name.” In some cases, an established name was used, for example, “Placer.” In other cases, a name was selected that emphasizes an aspect of the system that is characteristic of, and distinct from, the other systems, for example, “Chemical Weathering.” One system was named after the principal deposit type within it, namely “Porphyry Cu-Mo-Au.” In this case, it is important to realize that porphyry Cu-Mo-Au systems are much larger than porphyry Cu-Mo-Au deposits and encompass key aspects of the tectonic framework and all of the deposit types that occur within the system, as shown in figure 2. The second column is a brief “Synopsis” that provides information on the geotectonic setting of the system and a description of how it operates to form ore deposits containing various principal commodities and critical minerals. The third column is “Deposit types.” As described in the previous section, in some cases, different deposit types were grouped together under an overarching deposit name because they contain a similar assortment of principal commodities and critical minerals whereas those with distinct principal commodities and critical minerals were split out. The fourth column is a list of “Principal commodities” that generally are produced from, or explored for, in the deposit type. These are the commodities that govern the economics of mining and mineral processing. The fifth column is a list of “Critical minerals.” Those that have actually been produced from the deposit type are highlighted in bold type (for example, REE), whereas those that are enriched in the deposit type, but have not yet been produced, are listed in italics (for example, PGE). Critical minerals that are principal commodities, are listed in both columns. The sixth column is “Reference(s),” which cites publications that contain detailed descriptions of the system and deposit types upon which the entries in table 1 are based.

### Table Use

The hierarchical relationship between systems, deposits, commodities, and critical minerals in table 1 can be used to help define and prioritize Earth MRI focus areas for mapping projects in four ways.

First, if any part of a mineral system has been recognized by previous work, table 1 can be used to deduce the assortment of deposit types, principal commodities, and critical minerals that may be present in adjacent areas and under cover. Because information generally exists on the principal commodities and deposit types that are present in well-explored areas with a history of mining, table 1 can be used to infer the system type(s) and the critical minerals that may be present in mine waste, unmined resources, concealed deposit types under cover, or in deposit types that were removed by erosion. In areas with historical mining and exploration, these inferences have a higher degree of certainty because the known deposit types confirm that a mineral system actually operated in the area. The deposit types recognized at or near the surface also provide an indication of the level of exposure or tilting of the system.

Second, for system-based focus areas of the same type (for example, porphyry Cu-Mo-Au), the attributes of each area can be compared to identify those that are well endowed and (or) would benefit the most from Earth MRI mapping techniques.

Third, in some parts of the country, systems of different types and ages occur in the same geographic area, such that the system-based focused areas overlap. These areas are highly prospective and may benefit the most from Earth MRI mapping efforts.

Fourth, in frontier areas (for example, Alaska) or areas with extensive cover (for example, U.S. mid-continent), if a geotectonic setting, or terrane, is recognized that is known to host mineral systems of a given type elsewhere in the world (for example, Mesoproterozoic magmatic provinces), table 1 can be used to infer the deposit types, principal commodities, and critical minerals that may be present. In this case, Earth MRI maps of such terranes may detect evidence of mineral systems and lead to new discoveries.
Table 1. Systems-Deposits-Commodities-Critical Minerals Table for the Earth Mapping Resources Initiative.

[+, present (absent); —, not applicable; ?, maybe; Ag, silver; Al, aluminum; As, arsenic; Au, gold; B, boron; Ba, barium; Be, beryllium; Bi, bismuth; Br, bromine; Ca, calcium; Cd, cadmium; Co, cobalt; CO₂, carbon dioxide; Cs, cesium; Cr, chromium; Cu, copper; F, fluorine; Fe, iron; Ga, gallium; Ge, germanium; Hf, hafnium; Hg, mercury; I, iodine; IAEA, International Atomic Energy Agency; In, indium; IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; IS, intermediate sulfidation; K, potassium; LCT, lithium-cesium-tantalum; Li, lithium; Mg, magnesium; Mn, manganese; Mo, molybdenum; Na, sodium; Nb, niobium; Ni, nickel; NYF, niobium-yttrium-fluorine; P, phosphorus; Pb, lead; PGE, platinum group elements; R, replacement; Rb, rubidium; Re, rhenium; REE, rare earth elements; S, skarn; Sb, antimony; Sc, scandium; Se, selenium; Sn, tin; Sr, strontium; Ta, tantalum; Te, tellurium; Th, thorium; Ti, titanium; Tl, thallium; U, uranium; V, vanadium (in “Principal commodities” column); V, vein (in “Deposit types” column); W, tungsten; Y, yttrium; Zn, zinc; Zr, zirconium]

| System name | Synopsis | Deposit types | Principal commodities | Critical minerals¹ | Reference(s) |
|-------------|----------|---------------|-----------------------|-------------------|--------------|
| Placer (riverine-marine, residual-eluvial-alluvial-shoreline, paleo) | Placer systems operate in drainage basins and along shorelines where there is either topographic relief and gravity-driven turbulent flow of surface water or tidal and wind-driven wave action. Placer systems concentrate insoluble resistate minerals liberated from various rock types and mineral occurrences by the chemical breakdown and winnowing away of enclosing minerals by the movement of water. The distribution of insoluble resistate minerals is controlled by their size, density, and the turbulence of fluid flow. | Gold | Au | — | Sloan, 1964; Levson, 1995; Van Gosen and others, 2014; Sengupta and Van Gosen, 2016; Jones and others, 2017, Wang and others, 2021 |
| | | Uraninite, autunite-group minerals | U | U | |
| | | PGE | PGE | PGE |
| | | Cassiterite | Sn | Sn, Sc |
| | | Wolframite/scheelite | W | W, Sc |
| | | Barite | Barite | Barite |
| | | Fluorite | Fluorite | Fluorite |
| | | Monazite/xenotime | REE, Y, Th | REE |
| | | Columbite/tantalite | Nb, Ta | Nb, Ta, Mn |
| | | Zircon | Zr, Hf | Zr, Hf |
| | | Ilmenite/rutile/leucoxene | Ti | Ti, Sc |
| | | Magnetite/hematite/goethite | Fe | — |
| | | Diamond | Diamond gems and abrasive | — |
| | | Sapphire | Sapphire gems | — |
| | | Garnet | Garnet gems and abrasive | — |
### Chemical weathering (unsaturated zone, in situ)

Chemical weathering systems operate in stable areas of low to moderate relief with sufficient rainfall to chemically dissolve and concentrate elements present in various rock types and mineral occurrences by the downward percolation of surface water in the unsaturated zone. Chemical gradients cause different elements to be concentrated at different positions in the weathering profile and at the water table. Bauxite, Ni-laterite, and carbonatite laterite are restricted to tropical climatic zones; others form in temperate and arid climates. Dissolved uranium is reduced on carbonaceous material in lakes and swamps. Dissolved manganese precipitates at redox interfaces in lakes.

| System name | Synopsis | Deposit types | Principal commodities | Critical minerals | Reference(s) |
|-------------|----------|---------------|-----------------------|------------------|--------------|
| Nickel-cobalt laterite | Ni, Co | Co, Mn, Sc | Otton and others, 1990; Long and others, 1992; Marsh and others, 2013; Foley and Ayuso, 2015; Bruneton and Cuney, 2016; Sanematsu and Watanabe, 2016; IAEA, 2020; Wang and others, 2021 |
| Bauxite | Al | Al, Ga, REE | | |
| Clay | Kaolin | Ga, Li, REE | | |
| Carbonatite laterite | Nb, REE | Nb, REE, Sc | | |
| Regolith (Ion adsorption) REE | REE | REE, Sc | | |
| Surficial uranium | U | U | | |
| Lacustrine carbonaceous uranium | U | U | | |
| Coal uranium | U | U | | |
| Lacustrine manganese | Mn | Mn | | |
| Supergene (and laterite) gold | Au | — | | |
| Supergene silver | Ag | ? | | |
| Supergene lead | Pb | ? | | |
| Supergene zinc | Zn | ?Ga, Ga, In? | | |
| Supergene (and exotic) copper | Cu | ?Te, Bi? | | |
| Supergene cobalt | Co | Co | | |
| Supergene PGE | PGE | PGE | | |
| Supergene manganese | Mn | Mn, Co | | |
| Supergene iron | Fe | Mn | | |
Table 1. Systems-Deposits-Commodities-Critical Minerals Table for the Earth Mapping Resources Initiative.—Continued

| System name                  | Synopsis                                                                 | Deposit types             | Principal commodities | Critical minerals± | Reference(s)                          |
|------------------------------|--------------------------------------------------------------------------|---------------------------|-----------------------|--------------------|---------------------------------------|
| Meteoric recharge            | Meteoric recharge systems operate where oxidized meteoric groundwater displaces reduced connate water in sandstone aquifers that often contain volcanic ash or where such groundwater evaporates at the surface. As oxidized water descends through sandstone aquifers, it scavenges uranium and other elements from detrital minerals and (or) volcanic glass. Uranium and other elements precipitate at the redox front with reduced connate water, on carbonaceous material in the aquifers, or at the surface in calcrete by evaporation. In granite, descending oxidized meteoric groundwater leaches uranium from zircon, apatite, and other minerals that precipitate by reactions with ferrous Fe minerals. In ultramafic rocks, dissolved CO₂ in descending meteoric groundwater reacts with Mg-silicates to form magnesite, which may also precipitate in permeable sediment or rocks nearby. | Sandstone uranium         | U, V                   | U, V, Re, Sc, REE, Mn, Co, PGE | Zachmann and Johannes, 1989; Skirrow and others, 2009; Breit, 2016; Bruneton and Cuney, 2016; Hall and others, 2019; IAEA, 2020 |
|                              |                                                                          | Carbonate uranium         | U, V                   | U, V, Re, Sc, REE, Co, PGE |                                                      |
|                              |                                                                          | Calcrete uranium          | U, V                   | U, V, Sr            |                                                      |
|                              |                                                                          | Granite uranium           | U                      | U                   |                                                      |
|                              |                                                                          | Cryptocrystalline magnesite | Mg                   | Mg                  |                                                      |
| Meteорic convection          | Low-sulfidation Au-Ag deposits associated with mantle plume volcanic rocks form under relatively low oxygen and sulfur fugacities, and have low base metal contents and high Au/Ag ratios and selenium contents. Low-sulfidation deposits also occur along extensional fault zones that are not associated with proximal, coeval magmatic activity. | Low sulfidation epithermal gold-silver | Au, Ag, Hg, Sb | Sb, Te | Simmons and others, 2005; John and Henry, 2020 |
|                              |                                                                          | Low sulfidation epithermal antimony | Sb | Sb | |
|                              |                                                                          | Low sulfidation epithermal mercury | Hg | — | |

±, present (absent); —, not applicable; ?, maybe; Ag, silver; Al, aluminum; As, arsenic; Au, gold; B, boron; Ba, barium; Be, beryllium; Bi, bismuth; Br, bromine; Ca, calcium; Cd, cadmium; Co, cobalt; CO₂, carbon dioxide; Cs, cesium; Cr, chromium; Cu, copper; F, fluorine; Fe, iron; Ga, gallium; Ge, germanium; Hf, hafnium; Hg, mercury; I, iodine; IAEA, International Atomic Energy Agency; In, indium; IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; IS, intermediate sulfidation; K, potassium; LCT, lithium-cesium-tantalum; Li, lithium; Mg, magnesium; Mn, manganese; Mo, molybdenum; Na, sodium; Nb, niobium; Ni, nickel; NYF, niobium-yttrium-fluorine; P, phosphorus; Pb, lead; PGE, platinum group elements; R, replacement; Rb, rubidium; Re, rhenium; REE, rare earth elements; S, skarn; Sb, antimony; Sc, scandium; Se, selenium; Sn, tin; Sr, strontium; Ta, tantalum; Te, tellurium; Th, thorium; Ti, titanium; Tl, thallium; U, uranium; V, vanadium (in “Principal commodities” column); V, vein (in “Deposit types” column); W, tungsten; Y, yttrium; Zn, zinc; Zr, zirconium

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| System name                  | Synopsis                                                                 | Deposit types                          | Principal commodities                     | Critical minerals | Reference(s) |
|------------------------------|--------------------------------------------------------------------------|----------------------------------------|-------------------------------------------|------------------|---------------|
| Lacustrine evaporite         | Lacustrine evaporite systems operate in closed drainage basins in arid to hyperarid climatic zones. Elements present in meteoric surface, ground, and geothermal recharge water are concentrated by evaporation. As salinity increases, evaporite minerals typically precipitate in the following sequence: gypsum or anhydrite, halite, sylvite, carnallite, borate. Nitrates are concentrated in basins that accumulate sea spray. Residual brines enriched in lithium and other elements often accumulate in aquifers below dry lake beds. Li-clay and Li-B-zeolite deposits form where residual brine reacts with lake sediment, ash layers, or volcanic rocks. | Trona, Gypsum, Salt, Potash, Carnallite, Magnesite, Borate, Nitrate, Residual brine, Lithium clay, Lithium-boron zeolite | Trona (Na₂CO₃), Gypsum (CaSO₄•2H₂O), Salt (NaCl), Potash (KCl), Magnesite (MgCO₃), Borax, boric Acid, [Na, K, Ca, Mg][NO₃ nitrate, IO₃ iodate, BO₃ borate], Salt, potash, borax, boric acid, soda ash, sodium sulfate, Li, Rb, Cs, Mg, Mn, Sr, Br, I, W, Zn, Potash, Li, Mn, Rb, Cs, Mg, Sr, W | Potash, Mg, Li, | Dyni, 1991; Sheppard, 1991a,b; Williams-Stroud, 1991; Orris, 1995; Warren, 2010; Bradley and others, 2013; Hofstra and others, 2013b; Munk and others, 2016; Bradley and others, 2017b; Power and others, 2019 |
| Marine evaporite             | Marine evaporite systems operate in shallow restricted epicontinental basins in arid to hyperarid climatic zones. Sabkha dolomite and sedimentary magnesite form in coastal salt flats and lagoons. Elements present in seawater are concentrated by evaporation. As salinity increases, evaporite minerals typically precipitate in the following sequence: gypsum or anhydrite, halite, sylvite. Residual basin brines are enriched in conserved elements, such as Mg and Li. Incursion of freshwater or seawater can produce halite dissolution brines. | Sabkha dolomite, Sedimentary magnesite, Gypsum, Salt, Potash, Dissolution brine | Building stone, aggregate, Mg, Mg, Gypsum (CaSO₄•2H₂O), Salt (NaCl), Potash (KCl), Petroleum, salt (NaCl) | Mg, Mg, Potash | Raup 1991a, b; Mountney, 2005; Warren, 2010; Horn and others, 2017 |
Table 1. Systems-Deposits-Commodities-Critical Minerals Table for the Earth Mapping Resources Initiative.—Continued

| System name                      | Synopsis                                                                 | Deposit types                                                      | Principal commodities                                                                 | Critical minerals | Reference(s)                                                                   |
|----------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------|---------------------------------------------------------------------------------------|-------------------|--------------------------------------------------------------------------------|
| Basin brine path                 | Basin brine path systems emanate from marine evaporite basins and extend downward and laterally through permeable strata to discharge points in the ocean. Limestone is replaced by reflux dolomite at low temperatures and hydrothermal dolomite at high temperatures. Basin brines evolve to become ore fluids by scavenging metals from various rock types along gravity-driven flow paths. The mineralogy of the aquifers controls the redox and sulfidation state of the brine and the suite of elements that can be scavenged. Cu- and Pb-Zn sulfide deposits form where oxidized brines encounter reduced S. Unconformity U deposits form where oxidized brines are reduced. Ba and Sr deposits form where reduced brines encounter marine sulfate or carbonate. | Basin brine                                                | Petroleum, salt, potash, Li, Rb, Cs, Mg, Sr, Br, I, Zn | Potash, Li, Rb, Cs, Mg, Sr                                      | Cox and Singer, 2007; Skirrow and others, 2009; Alpine, 2010; Leach and others, 2010; Hayes and others, 2015; Emsbo and others, 2016a; Marsh and others, 2016; Johnson and others, 2017; Manning and Emsbo, 2018 |
|                                  |                                                                          | Reflux and hydrothermal dolomite                                   | Building stone, aggregate, Mg                                                        | Mg                |                                                                                   |
|                                  |                                                                          | Zinc-lead (MVT and sedex)                                           | Zn, Pb, Ag, Cu, Co                                                                    | Sn, Ge, Co, Ga, In |                                                                                   |
|                                  |                                                                          | Copper (sed-hosted and replacement)                                 | Cu, Co, Ag, Pb, Zn                                                                   | Co, PGE, Re, Ge, Ga, V, U |                                                                                   |
|                                  |                                                                          | Uranium (unconformity and breccia pipe)                             | U, V, Cu, Co, Mo, Re, Se, Sc, REE                                                        | U, V, Re, Sc, REE, Co |                                                                                   |
|                                  |                                                                          | Barite (replacement and bedded)                                     | Barite (witherite)                                                                   | Barite            |                                                                                   |
|                                  |                                                                          | Strontium (replacement and bedded)                                  | Sr (celestite, strontianite)                                                          | Sr                |                                                                                   |
| Marine chemocline (bath-tub rim) | Marine chemocline systems operate where basin brines discharge into the ocean. Consequent increases in bioproductivity produce metalliferous black shales. Changes in ocean chemistry (oceanic anoxic events) and development of chemoclines result in chemical sedimentation of phosphate and Mn and Fe carbonates and oxides. | Black shale                                              | Stone coal, petroleum, V, Ni, Mo, Au, PGE                                               | V, Re, PGE, Cr, U | Lefebure and Coveney, 1995; Force and others, 1999; Emsbo, 2000; Emsbo and others, 2016a; Marsh and others, 2016; Johnson and others, 2017; Cannon and others, 2017 |
Table 1. Systems-Deposits-Commodities-Critical Minerals Table for the Earth Mapping Resources Initiative.—Continued

| System name                     | Synopsis                                                                 | Deposit types | Principal commodities     | Critical minerals | Reference(s)                                                                 |
|---------------------------------|--------------------------------------------------------------------------|---------------|---------------------------|-------------------|-----------------------------------------------------------------------------|
| Petroleum                       | Ni and V in poprhyrin complexes are the most abundant metals in plant and animal remains in source rocks and in derived petroleum. Helium is produced by radioactive decay of U and Th in felsic igneous rocks and siliciclastic rocks derived from them. It is released by magmatic heat and (or) fracturing and accumulates in gas reservoirs below an impermeable seal. | Petroleum, Natural Gas | Asphalt, Petroleum, V, Ni | V                 | Magoon and Dow, 1994; Hunt, 1996; Brennan and East, 2015; Craddock and others, 2017; King, 2020 |
| Hybrid magmatic REE/basin brine path | This hybrid system operates where CO$_2$- and HF-bearing magmatic volatiles condense into basinal brines that replace carbonate with fluor spar ± barite, REE, Ti, Nb, and Be as in the Illinois-Kentucky Fluorspar District and Hicks Dome. | Fluorspar | Fluorite | Fluorite, barite, REE, Ti, Nb, Be | Plumlee and others, 1995; Denny and others, 2015, 2016; Hayes and others, 2017 |
| Arsenide                        | Arsenide systems form in continental rifts where deep-seated, oxidized, metal-rich, metamorphic basement brines ascend to shallow levels. Native elements (Ag, Bi, As), Ni-, Co- and Fe-mono-, di- and sulf-arsenides precipitate by reduction as hydrocarbons, graphite, or sulfide minerals are oxidized to form carbonates and barite. | Five element veins | Ag, As, Co, Ni, Bi, U, Sb | Co, Bi, U, As, Sb | Kissin, 1992, Markl and others, 2016; Burisch and others, 2017; Scharrer and others, 2019 |
| System name | Synopsis | Deposit types | Principal commodities | Critical minerals | Reference(s) |
|-------------|----------|---------------|-----------------------|------------------|--------------|
| Volcanogenic seafloor | Volcanogenic seafloor systems are driven by igneous activity along spreading centers, back-arc basins and magmatic arcs. In spreading centers and back-arc basins, seawater evolves to become an ore fluid by convection through hot volcanic rocks. In magmatic arcs, ore fluids exsolved from subvolcanic intrusions may mix with convecting seawater. Ore deposits form where hot reduced ore fluids vent into cool oxygenated seawater. Sulfides and sulfates precipitate in or near vents. Mn and Fe precipitate at chemoclines over wide areas in basins with seafloor hydrothermal activity. | Copper-zinc sulfide | Cu, Zn | Co, Bi, Te, In, Sn, Ge, Ga, Sb | Levson, 1995; Shanks and Thurston, 2012; Monecke and others, 2016; Cannon and others, 2017; DSM Observer, 2020 |
| Zinc-copper sulfide | Zn, Cu | Ge, Ga, Sb, Co, Bi, Te, In, Sn |
| Polymetallic sulfide | Cu, Zn, Pb, Ag, Au | Sn, Bi, Te, In, Ge, Ga, Sb, As |
| Barite | Barite | | | |
| Manganese oxide (layers, crusts, nodules) | Mn, Fe, Ni | Mn, Co, Ge, Te, REE, Sc |
| Algoma iron | Fe | | | |
| Orogenic | Metamorphic dewatering of sulfidic volcanic and (or) sulfidic, carbonaceous, and (or) calcareous siliciclastic sequences during exhumation with fluid flow along dilatant structures. Iron minerals in host rocks are often sulfidized. Metavolcanic host rocks often contain volcanogenic seafloor sulfide deposits. | Gold | Au, Ag | W, Te, As, Sb | Groves and others, 1998; Gray and Bailey, 2003; Goldfarb and others, 2005, 2016; Luque and others, 2014 |
| Antimony | Sb, Au, Ag | Sb |
| Mercury | Hg, Sb | Sb |
| Graphite | Graphite (lump) | Graphite (lump) |
| Coeur d’Alene-type | Metamorphic dewatering of moderately oxidized siliciclastic sequences during exhumation with fluid flow along dilatant structures. Metasedimentary host rocks may contain basin brine path Pb-Zn and Cu±Co deposits. | Polymetallic sulfide | Ag, Pb, Zn, Cu | Sb, Co, Ge, Ga, In | Wallace and Whelan, 1986; Leach and others, 1988, 1998; Beaudoin and Sangster, 1992, 1996; Balistrieri and others, 2002; Zartman and Smith, 2009; Hofstra and others, 2013a; Seal and others, 2017; IAEA, 2020 |
| Antimony | Sb | Sb |
| Uranium | U | U |
### Table 1. Systems-Deposits-Commodities-Critical Minerals Table for the Earth Mapping Resources Initiative.—Continued

| System name | Synopsis | Deposit types | Principal commodities | Critical minerals\(^1\) | Reference(s) |
|-------------|----------|---------------|-----------------------|-------------------------|--------------|
| Metamorphic | Metamorphic systems recrystallize rocks containing organic carbon or REE phosphate minerals or uranium minerals. Crystalline magnesite forms by carbonation of peridotite. | Graphite (coal or carbonaceous sed) | Graphite (amorphous and flake) | Graphite (amorphous and flake) | Sutphin, 1991a,b,c; Luque and others, 2014; McKinney and others, 2015; Sutherland and Cola, 2016; Robinson and others, 2017; Menzel and others, 2018; IAEA, 2020 |
| Porphyry Cu-Mo-Au | Porphyry copper-molybdenum-gold systems operate in oceanic and continental magmatic arcs with calc-alkaline compositions. Aqueous supercritical fluids exsolved from felsic plutons and the apices of subvolcanic stocks form a variety of deposit types as they move upward and outward, split into liquid and vapor, react with country rocks, and mix with groundwater. The broad spectrum of deposit types results from the large thermal and chemical gradients in these systems. | Greisen | Mo, W, Sn | W, Sn | Seedorff and others, 2005; John and others, 2010, 2017; Sillitoe, 2010; Taylor and others, 2012; John and Taylor, 2016; London, 2016; Wang and others, 2021 |
| Porphyry Cu-Mo-Au | Graphite (amorphous and flake) | Graphite (amorphous and flake) | Mo, W, Sn | W, Bi, Mn, Sc |
| Porphyry Cu-Mo-Au | Gneiss uranium | U | REE, U |
| Porphyry Cu-Mo-Au | S-R-V tungsten | W | W, Bi, Mn, Sc |
| Porphyry Cu-Mo-Au | Skarn iron | Fe, Cu | Ge |
| Porphyry Cu-Mo-Au | Skarn magnesite | Mg | Mg |
| Porphyry Cu-Mo-Au | R-V manganese | Mn | Mn, Co |
| Porphyry Cu-Mo-Au | Polymetallic sulfide S-R-V-IS | Cu, Zn, Cd, Pb, Ag, Au | Mn, Ge, Ga, In, Bi, Sb, As, W, Te |
| Porphyry Cu-Mo-Au | Distal disseminated silver-gold | Ag, Au | Sb, As |
| Porphyry Cu-Mo-Au | High-sulfidation gold-silver | Cu, Ag, Au | As, Sb, Te, Bi, Sn, Ga |
| Porphyry Cu-Mo-Au | Intermediate sulfidation antimony | Sb, Hg | Sb, As |
| Porphyry Cu-Mo-Au | Lithocap alunite | Al, K_2SO_4 (potash) | Al, K_2SO_4, Ga |
| Porphyry Cu-Mo-Au | Lithocap kaolinite | Kaolin | Ga |
Table 1. Systems-Deposits-Commodities-Critical Minerals Table for the Earth Mapping Resources Initiative.—Continued

| System name | Synopsis | Deposit types | Principal commodities | Critical minerals¹ | Reference(s) |
|-------------|----------|---------------|-----------------------|-------------------|--------------|
| Alkalic porphyry | Alkalic porphyry systems form in oceanic and continental magmatic arcs and in continental rifts by similar processes from fluids exsolved from more fractionated alkaline plutons and stocks. Resulting ore deposits tend to be more enriched in Au, Te, Bi, and V. | Greisen | Mo, Bi | Bi | Jensen and Barton, 2000; Kelley and Spry, 2016; Wang and others, 2021 |
| | S-R-V Tungsten | W | W, Bi, Mn, Sc |
| | Porphyry/skarn copper-gold | Cu, Mo, Au | PGE, Te, Bi |
| | Polymetallic sulfide S-R-V-IS | Au, Ag, Pb, Zn, Cu | Ge, Ga, In, Bi, Te |
| | Fluorspar | Fluorite | Fluorite |
| | Distal disseminated silver-gold | Ag, Au | Sb, As |
| | High sulfidation | Cu, Ag, Au | Te, Bi, As, Sb |
| | Low sulfidation | Au | Te, Bi, V, F |
| | Lithocap alunite? | Al, K₂SO₄ (potash) | Al, K₂SO₄, Ga |
| | Lithocap kaolinite? | Kaolin | Ga |
| Porphyry Sn (granite-related) | Granite-related porphyry Sn systems form in back-arc or hinterland settings by similar processes from fluids exsolved from more crustally contaminated S-type peraluminous plutons and stocks. At deep levels, LCT pegmatites emanate from plutons. Resulting ore deposits tend to be Cu and Mo poor and enriched in Li, Cs, Ta, Nb, Sn, W, Ag, Sb, and In. | Pegmatite LCT | Li-Cs-Ta | Li, Cs, Ta, Nb, Sn, Be, Sc | Panteleyev, 1996; Sillitoe and others, 1998; Černý and Ercit, 2005; Martin and De Vito, 2005; London, 2008, 2016; Bradley and others, 2017a; Kamilli and others, 2017; Hulsbosch, 2019; Wang and others, 2021 |
| | Greisen | Sn, W, Be | Sn, W, Be, Sc |
| | Porphyry/skarn | Sn, W, Be | Sn, W, Be, Sc |
| | Polymetallic sulfide S-R-V-IS | Cu, Zn, Pb, Ag, Au | Sn, Mn, Ge, Ga, In, Bi, Sh, As |
| | Distal disseminated silver-gold | Ag, Au | Sh, As |
| | High sulfidation | Cu, Ag, Au | Sn, Sh, As, Te, Bi |
| | Lithocap alunite | Al, K₂SO₄ (potash) | Al, K₂SO₄, Ga |
| | Lithocap kaolinite | Kaolin | Ga |
Table 1. Systems-Deposits-Commodities-Critical Minerals Table for the Earth Mapping Resources Initiative.—Continued

[+, present (absent); —, not applicable; ?, maybe; Ag, silver; Al, aluminum; As, arsenic; Au, gold; B, boron; Ba, barium; Be, beryllium; Bi, bismuth; Br, bromine; Ca, calcium; Cd, cadmium; Co, cobalt; CO₂, carbon dioxide; Cs, cesium; Cr, chromium; Cu, copper; F, fluorine; Fe, iron; Ga, gallium; Ge, germanium; Hf, hafnium; Hg, mercury; I, iodine; IAEA, International Atomic Energy Agency; In, indium; IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; IS, intermediate sulfidation; K, potassium; LCT, lithium-cesium-tantalum; Li, lithium; Mg, magnesium; Mn, manganese; Mo, molybdenum; Na, sodium; Nb, niobium; Ni, nickel; NYF, niobium-yttrium-fluorine; P, phosphorus; Pb, lead; PGE, platinum group elements; R, replacement; Rb, rubidium; Re, rhenium; REE, rare earth elements; S, skarn; Sb, antimony; Sc, scandium; Se, selenium; Sn, tin; Sr, strontium; Ta, tantalum; Te, tellurium; Th, thorium; Ti, titanium; Tl, thallium; U, uranium; V, vanadium (in “Principal commodities” column); V, vein (in “Deposit types” column); W, tungsten; Y, yttrium; Zn, zinc; Zr, zirconium]

| System name                  | Synopsis                                                                 | Deposit types   | Principal commodities | Critical minerals^1 | Reference(s)                  |
|------------------------------|--------------------------------------------------------------------------|-----------------|-----------------------|---------------------|-------------------------------|
| Reduced intrusion-related     | Reduced intrusion-related systems form in continental magmatic arcs by similar processes from fluids exsolved from calc-alkaline plutons and stocks that assimilated carbonaceous pyritic country rocks. Resulting ore deposits tend to be poor in Cu, Mo, and Sn and enriched in W, Au, Ag, Te, Bi, Sb, and As. | Pegmatite LCT   | Li-Cs-Ta              | Li, Cs, Ta, Nb, Sn, Be, Sc | Hart, 2007; Nutt and Hofstra, 2007; Luque and others, 2014; Wang and others, 2021 |
| Gold                         |                                                                          | Gold            | Au, Ag                | Te, Bi, Sb, As       |                               |
| Greisen-V tungsten            |                                                                          | Greisen-V tungsten | W, Mo                | W, Te, Bi, Re         |                               |
| Skarn copper-molybdenum-tungsten |                                                                          | Skarn copper-molybdenum-tungsten | W, Mo, Cu, Au, Ag   | W, Te, Bi, Re         |                               |
| Polymetallic sulfide S-R-V-IS |                                                                          | Polymetallic sulfide S-R-V-IS | Au, Ag, Pb, Zn, Cu | Mn, Ge, Ga, In, Bi, Sb, As |                               |
| Distal disseminated silver-gold |                                                                          | Distal disseminated silver-gold | Ag, Au              | Te, Bi, Sb, As       |                               |
| Intermediate sulfidation      |                                                                          | Intermediate sulfidation | Au, Ag, Pb, Zn, Cu  | Mn, Ge, Ga, In, Bi, Sb, As |                               |
| Intermediate sulfidation antimony |                                                                          | Intermediate sulfidation antimony | Sb                  | Sb                       |                               |
| Graphite                     |                                                                          | Graphite        | Graphite (lump)       | Graphite (lump)       |                               |
| Carlin-type                   | Carlin-type systems occur in continental magmatic arcs but are remote from subjacent stocks and plutons. Consequently, ore fluids consist largely of meteoric water containing volatiles discharged from deep intrusions. Ore fluids scavenge elements from carbonaceous pyritic sedimentary rocks as they convect through them. Gold ore containing disseminated pyrite forms where acidic reduced fluids dissolve carbonate and sulfidize Fe-bearing minerals in host rocks. As, Hg, and TI minerals precipitate by cooling. Stibnite precipitates with quartz by cooling from Au-, As-, Hg-, and TI-depleted fluids. | Gold            | Au, Ag, Hg            | As, Sb                     | Hofstra and Cline, 2000; Goldfarb and others, 2016; Muntean, 2018 |
| Antimony                     |                                                                          | Antimony        | Sb                    | Sb                       |                               |
| Arsenic-thallium-mercury      |                                                                          | Arsenic-thallium-mercury | As, Tl, Hg           | As                       |                               |
| System name       | Synopsis                                                                 |
|-------------------|--------------------------------------------------------------------------|
| Climax-type       | Climax-type systems occur in continental rifts with hydrous bimodal magmatism. Aqueous supercritical fluids exsolved from A-type topaz rhyolite plutons, and the apices of subvolcanic stocks form a variety of deposit types as they move upward and outward, split into liquid and vapor, react with country rocks, and mix with groundwater. The broad spectrum of deposit types results from the large thermal and chemical gradients in these systems. At deep levels, NYF pegmatites emanate from plutons. |
| Pegmatite NYF     | Nb, Y, F, Be                                                              |
| Greisen           | W, Sn, Bi, Be, Sc                                                         |
| Porphyry molybdenum | Mo, W, Sn                                                                |
| Skarn molybdenum  | W, Sn, Re, REE, Sc                                                        |
| Greisen-S-R beryl,ium | Be, F                                                                    |
| Polymetallic sulfide S-R-V-IS | Cu, Zn, Pb, Ag, Au                                                       |
| Distal disseminated silver-gold | Ag, Au                                                                    |
| High sulfidation  | Sn, Sh, As, Te, Bi                                                        |
| Lithocap alunite  | Al, K₂SO₄ (potash)                                                        |
| Lithocap kaolinite| Ga                                                                       |
| Fluorspar         | Fluorite                                                                  |
| Volcanogenic beryl,ium | Be, U                                                                     |
| Volcanogenic uranium | U, Li                                                                     |
| Rhoylite tin      | Sn                                                                       |
| IOA-IOCG          | IOA-IOCG systems form in both subduction- and rift-related magmatic provinces. IOA deposits form as hot brine discharged from subvolcanic mafic to intermediate composition intrusions reacts with cool country rocks. Albitite uranium deposits form at deeper levels where brines albitize country rocks. IOCG deposits form on the roof or periphery of IOA mineralization at lower temperatures, often with involvement of external fluids. Polymetallic skarn, replacement, and vein deposits occur outboard from IOCG deposits. Mn replacement and lacustrine Fe deposits form near or at the paleosurface. |
| Albite uranium    | U                                                                        |
| Iron oxide apatite| Fe                                                                       |
| Iron oxide copper gold | Cu, Au, U, Co, Se                                                        |
| Skarn iron        | Fe, P                                                                    |
| Polymetallic sulfide S-R-V | Ni, Co, Mo, Cu, Zn, Pb, Ag, Au                                           |
| Replacement manganese | Mn                                                                       |
| Lacustrine iron   | Fe                                                                       |

1. ±, present (absent); —, not applicable; ?, maybe; Ag, silver; Al, aluminum; As, arsenic; Au, gold; B, boron; Ba, barium; Be, beryllium; Bi, bismuth; Br, bromine; Ca, calcium; Cd, cadmium; Co, cobalt; CO₂, carbon dioxide; Cs, cesium; Cr, chromium; Cu, copper; F, fluorine; Fe, iron; Ga, gallium; Ge, germanium; Hf, hafnium; Hg, mercury; I, iodine; IAEA, International Atomic Energy Agency; In, indium; IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; IS, intermediate sulfidation; K, potassium; LCT, lithium-cesium-tantalum; Li, lithium; Mg, magnesium; Mn, manganese; Mo, molybdenum; Na, sodium; Nb, niobium; Ni, nickel; NYF, niobium-yttrium-fluorite; P, phosphorus; Pb, lead; PGE, platinum group elements; R, replacement; Rb, rubidium; Re, rhenium; REE, rare earth elements; S, skarn; S, skarn; Sb, antimony; Sc, scandium; Se, selenium; Sn, tin; Sr, strontium; Ta, tantalum; Te, tellurium; Th, thorium; Ti, titanium; Tl, thallium; U, uranium; V, vanadium (in “Principal commodities” column); V, vein (in “Deposit types” column); W, tungsten; Y, yttrium; Zn, zinc; Zr, zirconium

[Černý and Ercit, 2005; Martin and De Vito, 2005; London, 2008, 2016; Ludington and Plumlee, 2009; Breit and Hall, 2011; Foley and others, 2012; Hofstra and others, 2014; London, 2016; Audétat and Li, 2017; Wang and others, 2021]
Table 1. Systems-Deposits-Commodities-Critical Minerals Table for the Earth Mapping Resources Initiative.—Continued

[±, present (absent); —, not applicable; ?, maybe; Ag, silver; Al, aluminum; As, arsenic; Au, gold; B, boron; Ba, barium; Be, beryllium; Bi, bismuth; Br, bromine; Ca, calcium; Cd, cadmium; Co, cobalt; CO₂, carbon dioxide; Cs, cesium; Cr, chromium; Cu, copper; F, fluorine; Fe, iron; Ga, gallium; Ge, germanium; Hf, hafnium; Hg, mercury; I, iodine; IAEA, International Atomic Energy Agency; In, indium; IOA, iron oxide-apatite; IOCG, iron oxide-copper-gold; IS, intermediate sulfidation; K, potassium; LCT, lithium-cesium-tantalum; Li, lithium; Mg, magnesium; Mn, manganese; Mo, molybdenum; Na, sodium; Nb, niobium; Ni, nickel; NYF, niobium-yttrium-fluorine; P, phosphorus; Pb, lead; PGE, platinum group elements; R, replacement; Rb, rubidium; Re, rhenium; REE, rare earth elements; S, skarn; Sr, strontium; Ta, tantalum; Te, tellurium; Th, thorium; Ti, titanium; U, uranium; V, vanadium; Y, yttrium; Zn, zinc; Zr, zirconium]

| System name | Synopsis | Deposit types | Principal commodities | Critical minerals¹ | Reference(s) |
|-------------|----------|---------------|-----------------------|--------------------|--------------|
| Magmatic REE | Magmatic REE systems typically occur in continental rifts or along translithospheric structures. REE and other elements in mantle-derived ultrabasic, alkaline, and peralkaline (agpaitic) intrusions are enriched by fractionation and separation of immiscible carbonate melts ± saline hydrothermal liquids. Exsolved magmatic fluids or heated external fluids may deposit REE and other elements in adjacent country rocks. | Peralkaline syenite/ granite/rhyolite/ alaskite/pegmatites | REE, Y, Zr, Hf, Nb, Ta, Be, U, Th, Cu | REE, Zr, Hf, Nb, Ta, Be, U, V, Te, fluorite | Verplanck and others, 2014, 2016; Dostal, 2016, 2017; Wang and others, 2021 |
| Carbonatite | REE, P, Y, Nb, Ba, Sr, U, Th, Cu | REE, Nb, Sc, U, Sr, Ba, P, Cu, Zr, magnetite, vermiculite, fluorite |
| Phosphate | REE, P | REE |
| Fluorspar | Flourite | Flourite, barite, Ti, Nb, Zr, REE, Sc, U, Be |
| Chromite | Cr | Cr |
| Nickel-copper-PGE sulfide | Ni, Cu, Co, PGE, Ag, Au, Se, Te | Co, PGE, Te |
| PGE (low sulfide) | PGE | PGE |
| Iron-titanium oxide | Fe, Ti, V, P | Ti, V, REE |

¹Elements in bold have been produced from some deposits, whereas those in italics are potential critical minerals.
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