Natural Resources Research Institute

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NRRI TECHNICAL REPORT

A BIBLIOGRAPHY OF PUBLISHED RESEARCH IN MINNESOTA RELATED TO THE STATE'S MINERAL POTENTIAL: JUNE 2022

Submitted by:

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EXECUTIVE SUMMARY

The Minnesota Geological Survey (MGS) was provided funding from the United States Geological Survey (USGS) via the FY 2021 National Geological and Geophysical Data Preservation Program for the "FY21 Minnesota Geological and Geophysical Data Preservation Program." The program included two priorities that collectively involved 11 separate Projects:

Priority 1: Data Preservation

- Project 1: Preservation of MGS Field Data
- Project 2: Preservation of MGS Cuttings
- Project 3: Minnesota Drill Core Library Inventory, Phase I
- Project 4: Data Preservation Workshop

Priority 2: Mineral Potential-Related Information

- Project 5: State Compilation of Mineral Deposits / Districts
- Project 6: Contribute Data to USGS Map Compilation of Focus Areas
- Projects 7 and 8: State Compilation of Borehole Data with Metadata to NDC
- Project 9: Update Geologic Map Database
- Project 10: USGS Critical Minerals Workshop
- Project 11: Strategic Plan for Critical Minerals

As a Component of Priority 2, Project 6, "Contribute Data to USGS Map Compilation of Focus Areas," the Natural Resources Research Institute (NRRI) was subcontracted by the Minnesota Geological Survey (MGS) to prepare a bibliography indicating published geological, geochemical, and geophysical research specific to Minnesota that supports inference of Mineral potential. Matching funding was provided from the NRRI University of Minnesota Permanent University Trust Fund to complete this work. The publications that form the basis of this bibliography are in NRRI Technical Summary Report "Duluth Complex Geological Bibliography" (Hauck, 2017), "A Bibliography of Published Research in Minnesota Related to the State's Mineral Potential" (Hudak, 2020), and "Minnesota Data Preservation Report for 2019/2020: Updated Data Inventory, Preservation of Pillsbury Hall Rock Collections and Documentation, Assembly of Mineral Potential Related Information (Thorleifson, 2020). Matching funding was provided from the NRRI University of Minnesota Permanent University Trust Fund to complete this work.

The following bibliography has been organized utilizing the USGS Mineral Systems approach for critical minerals inventory, research and assessment (Hofstra, 2019; Hofstra and Kreiner, 2020). As Minnesota has a preserved Geologic history that spans greater than 3.6 billion years, a wide variety of geological Processes encompassing a number of Mineral Systems have been active within the State. These include Chemical Weathering, Placer, Meteoric Recharge, Marine Chemocline, Volcanogenic Seafloor, Orogenic, Metamorphic, IOA-IOCG, and Mafic Magmatic. This bibliography includes references specific to each of these Mineral Systems, as well as a list of references Related to potential by-products, recycling, and carbon Mineralization publications focused on Minnesota resources.

TABLE OF CONTENTS

INTRODUCTION

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Since Minnesota has a preserved geological history that spans greater than 3.6 billion years, and because a wide variety of geological Processes have been active over this geological history, Mineral potential exists within the State in many of the Mineral Systems. Utilizing the Mineral Systems classification recently developed by the USGS and others (Hofstra, 2019; Hofstra et al., 2021; Hofstra and Kreiner, 2020), Minnesota has Mineral potential in several Mineral Systems, including Chemical Weathering, Placer, Meteoric Recharge, Marine Chemocline, Volcanogenic Seafloor, Orogenic, Metamorphic, IOA-IOCG, and Mafic Magmatic.

It is worth noting that a large number of references Related to the "Mafic Magmatic" Mineral System in the current bibliography were derived from the recently published NRRI Technical Summary Report "Duluth Complex Geological Bibliography" (Hauck, 2017). As well, a significant number of references

Related to rare earth Element (REE) Mineral potential in Minnesota were derived from the NRRI Technical Report "Geological and Geochemical Reconnaissance for Rare Earth Element Mineralization in Minnesota" (Hauck et al., 2014).

A Component of the upcoming USGS Earth MRI program will evaluate waste materials as a potential source for critical minerals. As such, this bibliography has included a section with references associated with potential By-Products/Recycling resources. Many of these have been identified on the Natural Resources Research Institute (NRRI) Resources and Publications website (https://www.nrri.umn.edu/research/publications). Also, since social license is becoming an important consideration Related to Development of Mineral resources in Minnesota, the U.S., and worldwide, relevant references Related to this topic have also been included in a section in this bibliography called "Social License."

METHODS

The USGS has recently developed a new minerals System approach for critical minerals inventory, research, and assessment (https://www.usgs.gov/energy-and-minerals/mineral-resources-program/science/systems-approach-critical-minerals-inventory?qt-science_center_objects=0#qt-science_center_objects; Hofstra, 2019; Hofstra and Kreiner, 2020). The following bibliography is organized utilizing the minerals System classification scheme presented in Hofstra and Kreiner, 2020.

References included in this bibliography were obtained by utilizing a variety of online scientific search Databases, including Academic One File, Geobase, Science Direct, SCOPUS, Wiley Online Library, and Google Scholar. As well, Regional university thesis archives (including at the University of Minnesota Twin Cities and the University of Minnesota Duluth) were used to obtain recent and historical graduate thesis references. Finally, significant research has been presented at Institute on Lake Superior Geology (ILSG) conferences. References associated with abstract and field trip volumes of the ILSG were obtained from the ILSG website (https://www.lakesuperiorgeology.org/) and the most recent Program and Abstracts volume from the 68th Annual Meeting of the ILSG (Easton, 2022).

BIBLIOGRAPHY OF MINNESOTA-SPECIFIC MINERAL POTENTIAL RESEARCH

General References for Minnesota Geologic Maps and Other Mineral Potential Information and Data

Large collections of references specific to Minnesota Geology, Minnesota Mineral Deposits, and Minnesota Mineral potential can be found by accessing the websites of the MGS, the Minnesota Department of Resources Department of Lands and Minerals (MNDNR), and the NRRI. As well, the website for the Minnesota Minerals Coordinating Committee (MCC) contains links to a variety of research focused on diversification of Mineral resources within Minnesota.

The MGS website (https://cse.umn.edu/mgs) contains a large collection of geological Maps, geological reports, spatial Datasets, and geophysical Data that is available for public download. These can be found by searching the "Maps, Data & Publications" section of the MGS home page. Of particular importance for understanding and evaluating Minnesota Mineral potential are the following Components of this website:

- Map and Data Library (https://conservancy.umn.edu/handle/11299/708)
- Open Data Portal (https://mngs-umn.opendata.arcgis.com/)
- Find By Location (https://umn.maps.arcgis.com/apps/MapSeries/index.html?appid=98d153d598e54bc28c06b46ed35f896d)
- Field Notebook Collection (https://archives.lib.umn.edu/repositories/14/resources/1675)
- Map Sales (https://cse.umn.edu/mgs/map-sales)

The MNDNR Department of Lands and Minerals website also contains a wide variety of resources Related to Minnesota Mineral potential (https://www.dnr.state.mn.us/lands_minerals/index.html). Three main headings (Lands, Minerals, and Publications and Data) on this web page provide links to key information. These include:

- Land Heading: Acquisitions, Appraisal Management, Conservation Easements, Easements, Land Exchange, Land Sales, Leases (non-mineral), Tax Forfeited Land Reviews, and Utility Crossing Licenses;

- Minerals Heading: Aggregate Maps, Aggregate Leasing, Exploration Plans, Metallic Minerals Lease Sale, Minarchive, Mineland Reclamation, Mineral Projects and Data Releases, Non-Ferrous Metallic Minerals, PolyMet, Reclamation Research, State Mineral Leases, Underground Mine Mapping, Waters Programe;

- Publications and Data Heading: Publications, GIS Data and Maps, Web Maps, Reclamation Research, Aggregate Maps, DNR Corescan Project, Land Sales, Mineral Projects and Data Releases, Drill Core Library, Lehmann Exploration Collection, Minarchive and Underground Mine Mapping.

The NRRI is an applied research institute located in Duluth, Minnesota that comprises part of the University of Minnesota Research Enterprise. Since its inception in the mid-1980s, the NRRI has completed a variety of Mineral resource characterization, Mineral resource evaluation, Mineral potential, summary of Mineral Exploration, and minerals Processing research at its Duluth Lab and Coleraine Lab. Reports, Geologic Maps, and Data releases associated with this research can be found at the NRRI Resources and Publications website (https://www.nrri.umn.edu/research/publications).

The MCC (http://mcc.mn.gov/) is responsible for the management and coordination of Minnesota's Mineral Diversification Program Projects. The Mineral Diversification Program was created by the Minnesota Legislature in 1987 to "provide for the diversification of the State's Mineral economy through long term support of Mineral Exploration, Development, production, and commercialization." The Minnesota Minerals Coordinating Committee Resources webpage (http://mcc.mn.gov/resources.html) provide links to obtain a variety of reports and Data, including Projects, GIS Data, Maps, links, and information regarding the MNDNR Drill Core Library, which is located in Hibbing, Minnesota.

Minnesota Mineral Potential References for USGS Mineral Systems

Chemical Weathering

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.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Ni-Co Laterite	Ni, Co	Co, Sc
Bauxite	Al	Al, Ga, REE
Kaolinite	Kaolin	*Ga*
Carbonatite Laterite	Nb, REE	Nb, REE
Regolith (Ion Adsorption) REE	REE	REE
Uranium	U	U
Supergene(& laterite) Gold	Au	
Supergene Silver	Ag	?
Supergene Lead	Pb	?
Supergene Zinc	Zn	? *Ge, Ga, In*?
Supergene (& exotic) Copper	Cu	? *Te, Bi* ?
Supergene Cobalt	Co	Co
Supergene PGE	PGE	PGE
Supergene Manganese	Mn	Mn, Co
Supergene Iron	Fe	

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Placer

Placer Systems operate in drainage basins and along shorelines where topographic relief contributes to Gravity-driven turbulent flow of surface water, or tidal- and wind-driven wave action occurs. 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.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Gold	Au	
Uraninite, Autunite-group minerals	U	U
PGE	PGE	PGE
Cassiterite	Sn	Sn
Wolframite/Scheelite	W	W
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
Diamond	diamond gems and abrasive	
Sapphire	sapphire gems	
Garnet	garnet gems and abrasive	

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Lacustrine Evaporite

Lacustrine evaporite Systems operate in closed drainage basins in arid to hyper-arid climatic Zones. Elements present in meteoric surface, ground, and geothermal recharge 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 zeolite Deposits form where residual brine reacts with ash layers or volcanic Rocks.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Trona	Soda Ash (Na2CO3)	
Gypsum	Gypsum (CaSO4•2H2O)	
Salt	Salt (NaCl)	
Potash	Potash (KCl)	Potash
Carnallite	KMgCl3•6H2O	Potash, Mg
Borate	Borax, Boric Acid	*Li*
Nitrate	[Na, K, Ca, Mg][NO3, IO3, BO3]	*Mg*
Residual Brine	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
Lithium Clay	Li	Li
Li-B Zeolite	zeolite, B, Li	*Li*

No identified references in Minnesota.

Meteoric Recharge

Meteoric recharge Systems operate where oxidized meteoric groundwater displaces reduced connate water in sandstone aquifers that often contain volcanic ash or 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 and on carbonaceous material in the aquifers or at the surface in calcrete by evaporation.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Sandstone Uranium	U, V	U, V, Re, Sc, REE, Co, PGE
Calcrete Uranium	U, V	U, V, Sr

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Marine Evaporite

Marine evaporite Systems operate in shallow restricted epicontinental basins in arid to hyper-arid climatic Zones. 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. Incursion of fresh water or seawater can produce halite dissolution brines.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Gypsum	Gypsum ($CaSO_4$)· $2H_2O$	
Salt	Salt (NaCl)	
Potash	Potash (KCl)	Potash
Basin Brine	Petroleum, Salt, Potash, Li, Rb, Cs, Mg, Sr, Br, I, Zn	Potash, Li, Rb, Cs, Mg, Sr
Dissolution Brine	Petroleum, Salt (NaCl)	

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Basin Brine Path

Basin brine path Systems emanate from marine evaporite basins and extend laterally through permeable strata to discharge points in the ocean. 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-Co and Pb-Zn Sulfide Deposits form where oxidized brines encounter reduced S. Unconformity U Deposits form where reduced brines are oxidized. Ba and Sr Deposits form where reduced brines encounter marine sulfate or carbonate.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Hydrothermal Dolomite	Building stone, aggregate	*Mg*
Zn-Pb-Ag (MVT & Sedex)	Zn, Pb, Ag, Cu, Co	Sn, Ge, Co, Ga, In
Cu-Co (Sed-hosted)	Cu, Co	Co, PGE, Re
Cu-Co (low-temp replacement)	Cu, Co	Co, Ge, Ga
Unconformity Uranium	U, V, Cu, Co, Mo, Re, Se, Sc, REE	U, V, Re, Sc, REE, Co
Barite (Replacement & Bedded)	barite (witherite)	Barite
Sr (Replacement & Bedded)	Sr (celestite, strontianite)	Sr

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Marine Chemocline

Marine chemocline Systems operate where basin brines discharge into the ocean. Consequent increases in bioproductivity produce metalliferous black shales, and changes in ocean chemistry result in chemical sedimentation of phosphate and Mn and Fe carbonates and oxides.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Black shale	Stone coal, Petroleum, V, Ni, Mo, Au, PGE	V, Re, PGE
Phosphate	Phosphate fertilizer	*REE, U*
Fe-Mn	Fe, Mn, Co	Mn, Co
Superior Fe	Fe	

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Hybrid Peralkaline Intrusion or Carbonatite/Basin Brine Path

This hybrid System operates where HF-bearing Magmatic volatiles condense into basinal brines that replace carbonate with fluorspar ± REE, Ti, Be as in the IL-KY Fluorspar district and Hicks Dome.

Deposit Types	**Principal Commodities**	**Critical Minerals/*Potential CMs***
Fluorospar (Replacement)	Fluorite	Fluorite, REE, Ti, Be

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Arsenide

Continental Rifting promotes ascent of deep-seated Metamorphic metal-rich basement brine and mixing with sulphide-bearing basinal brine and natural gas. Fluid mixing and oxidation of methane induced precipitation of native metals, arsenides, and calcite.

Deposit Types	**Principal Commodities**	**Critical Minerals/*Potential CMs***
Five Element Veins	Ag, As, Co, Ni, Bi, U, Sb	Co, Bi, U, As, Sb

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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 over wide Areas in basins with seafloor hydrothermal activity.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Cu-Zn Sulfide	Cu, Zn	*Co, Bi, Te, In, Sn, Ge, Ga, Sb*
Zn-Cu 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	*barite*
Mn oxide (layers and nodules)	Mn, Fe	Mn, Co, Ge
Algoma Fe	Fe	?

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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. Volcanic host Rocks often contain VMS Deposits.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Gold	Au, Ag	W, Te, As, Sb
Antimony	Sb, Au, Ag	Sb
Mercury	Hg, Sb	*Sb*
Graphite	graphite (lump)	graphite (lump)

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Coeur d'Alene Type

Metamorphic dewatering of moderately oxidized siliciclastic sequences during exhumation with Fluid flow along dilatant Structures. Sedimentary host Rocks may contain basin brine path Pb-Zn and Cu±Co Deposits.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Polymetallic Sulfide	Ag, Pb, Zn, Cu	Sb, Co, Ge, Ga, In
Antimony	Sb	Sb

No identified references in Minnesota.

Metamorphic

Metamorphism of Rocks containing organic carbon or REE phosphate minerals.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Graphite (coal or carbonaceous sed)	graphite (amorphous and flake)	graphite (amorphous and flake)
Gneiss REE (monazite, xenotime)	Th, U, REE, Y	REE, U

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Porphyry Cu-Mo-Au

Porphyry copper 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 ground water. The broad spectrum of Deposit types results from the large thermal and chemical gradients in these Systems.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Pegmatite?	Li, Cs, Ta	Li, Cs, Ta, Nb, Be
Greisen	Mo, W, Sn	*W, Sn*
S-R-V Tungsten	W	W, Bi, Mn
Porphyry/Skarn Molybdenum	Mo, W, Sn	*W, Re, Bi*
Porphyry/Skarn Copper	Cu, Ag, Au, Mo	PGE, Te, Re, Bi, U
Skarn Iron	Fe, Cu	*Ge*
Polymetallic Sulfide S-R-V-IS	Cu, Zn, Pb, Ag, Au	*Mn, Ge, Ga, In, Bi, Sb, As, W, Te*
Distal Disseminated Ag-Au	Ag, Au	*Sb, As*
High sulfidation Au-Ag	Cu, Ag, Au	*As, Sb, Te, Bi, Sn, Ga*
Lithocap Alunite	Al, K2SO4	*Al, K2SO4, Ga*
Lithocap Kaolinite	kaolin	*Ga*

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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 alkalic plutons and stocks. Resulting ore Deposits tend to be more enriched in Au, Te, Bi, and V.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Pegmatite?	?	
Greisen	Mo, Bi	Bi
Porphyry/Skarn Cu-Au	Cu, Mo, Au	PGE, Te, Bi
Polymetallic Sulfide S-R-V-IS	Au, Ag, Pb, Zn, Cu	Ge, Ga, In, Bi, Te
Distal Disseminated Ag-Au	Ag, Au	*Sb, As*
High Sulfidation	Cu, Ag, Au	*Te, Bi, As, Sb*
Low Sulfidation	Au	*Te, Bi, V, F*
Lithocap Alunite?	Al, K2SO4	*Al, K2SO4, Ga*
Lithocap Kaolinite?	kaolin	*Ga*

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Porphyry Sn

Porphyry Sn Systems form in back arc Settings by similar Processes from Fluids exsolved from more crustally contaminated S-type plutons and stocks. Resulting ore Deposits tend to be Cu and Mo poor and enriched in Li, Sn, Ag, In and Sb.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Pegmatite (LCT)	Li-Cs-Ta	**Li, Cs, Ta, Nb, Be**
Greisen	Sn, W	**Sn, W**
Porphyry/Skarn Tin	Sn, W	**Sn, W**
Polymetallic Sulfide S-R-V-IS	Cu, Zn, Pb, Ag, Au	*Mn, Ge, Ga, In, Bi, Sb, As*
Distal Disseminated Ag-Au	Ag, Au	*Sb, As*
High Sulfidation	Cu, Ag, Au	*Sb, As, Te, Bi*
Lithocap Alunite	Al, K2SO4	*Al, K2SO4, Ga*
Lithocap Kaolinite	kaolin	*Ga*

Dicken, C., 2020, GIS for Focus Areas of Potential Domestic Resources of 11 Critical Minerals—Aluminum, Cobalt, Graphite, Lithium, Niobium, Platinum Group Elements, Rare Earth Elements, Tantalum, Tin, Titanium, and Tungsten (version 2.0, August 2020): USGS, Mineral Resources, Online Spatial Data, Earth MRI. https://mrdata.usgs.gov/earthmri/focus-Areas/metadata/FocusAreas_Phase2_v2.faq.html

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, Sn and enriched in W, Au, Ag, Te, Bi, Sb and As.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Gold	Au, Ag	*Te, Bi, Sb, As*
Cu-Mo-W Skarn	W, Mo, Cu, Au, Ag	*W, Te, Bi, Re*
Polymetallic Sulfide S-R-V-IS	Au, Ag, Pb, Zn, Cu	*Mn, Ge, Ga, In, Bi, Sb, As*
Distal Disseminated Ag-Au	Ag, Au	*Te, Bi, Sb, As*
Intermediate Sulfidation	Au, Ag, Pb, Zn, Cu	*Mn, Ge, Ga, In, Bi, Sb, As*
Graphite	graphite (lump)	graphite (lump)

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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 with volatiles discharged from deep Intrusions that scavenged Elements from carbonaceous pyritic sedimentary Rocks as it convected through them. Gold ore containing disseminated pyrite formed where acidic reduced Fluids dissolve

carbonate and sulfidize Fe-bearing minerals in Country Rocks. As, Hg, Tl minerals precipitated by cooling. Stibnite precipitated with quartz by cooling from Au, As, Hg, Tl depleted Fluids.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Gold	Au, Ag, Hg	*As, Sb*
Antimony	Sb	Sb
As-Tl-Hg	As, Tl, Hg	As

No identified references in Minnesota.

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 ground water. The broad spectrum of Deposit types results from the large thermal and chemical gradients in these Systems.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Pegmatite (NYF)	Nb, Y, F, Be	Nb, Ta, Be
Greisen	Mo, W, Sn	W, Sn, Bi
Porphyry Molybdenum	Mo, W, Sn	W, Sn, Re
Mo Skarn	Mo, W, Sn	*W, Sn*
Polymetallic Sulfide S-R-V-IS	Cu, Zn, Pb, Ag, Au	*Mn, Ge, Ga, In, Bi, Sb, As*
Distal Disseminated Ag-Au	Ag, Au	*Sb, As*
Lithocap alunite	Al, K2SO4	Al, K2SO4, Ga
Lithocap kaolinite	Kaolin	*Ga*
Fluorspar	Fluorite	Fluorite
Volcanogenic Berylium	Be, U	Be, U, Li
Volcanogenic Uranium	U	U, Li, Be

Dicken, C., 2020, GIS for Focus Areas of Potential Domestic Resources of 11 Critical Minerals—Aluminum, Cobalt, Graphite, Lithium, Niobium, Platinum Group Elements, Rare Earth Elements, Tantalum, Tin, Titanium, and Tungsten (version 2.0, August 2020): USGS, Mineral Resources, Online Spatial Data, Earth MRI. https://mrdata.usgs.gov/earthmri/focus-Areas/metadata/FocusAreas_Phase2_v2.faq.html

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 from 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 out board from IOCG Deposits. Mn replacement and lacustrine Fe Deposits form near or at the paleosurface.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Albitite Uranium	U	U
Iron Oxide Apatite (IOA)	Fe	*REE*
Iron Oxide Copper Gold (IOCG)	Cu, Au, U, Co, Se	U, Co
Skarn Fe	Fe, P	*REE, Ge*
Polymetallic S-R-V	Ni, Co, Mo, Cu, Zn, Pb, Ag, Au	Co, Re, Ge, Ga, In, Bi, Sb, As
Replacement Mn	Mn	Mn, Co
Lacustrine Iron	Fe	

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Magmatic REE

Mineralization associated with basic (e.g. Gabbro) or ultrabasic (e.g. pyroxenite, Troctolite, Anorthosite) plutonic or intrusive Igneous Rocks, often in large Igneous provinces Related to mantle plumes or meteorite impact. Nickel-copper stratiform ores result from settling and accumulation of immiscible Sulfide liquids in basic layered Intrusions and ultramafic flows and also may be important sources of PGEs. Such ores may also occur as podiform accumulations in plutonic sections of ancient obduction-related or Rift-related ophiolites.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Peralkaline syenite/granite/rhyolite + alaskite/pegmatites	REE, Y, Zr, Hf, Nb, Ta, Be, U, Th, Cu	REE, Zr, Hf, Nb, Ta, Be, U
Carbonatite	REE, P, Y, Nb, Ba, Sr, U, Th, Cu	*REE, Nb, Sc, U, Sr, Ba, P, Cu, Zr, magnetite, vermiculite*
Phosphate	REE, P	

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Mafic Magmatic

Mineralization associated with basic (e.g. Gabbro) or ultrabasic (e.g. pyroxenite, Troctolite, Anorthosite) plutonic or intrusive Igneous Rocks, often in large Igneous provinces Related to mantle plumes or meteorite impact. Nickel-copper stratiform ores result from settling and accumulation of immiscible Sulfide liquids in basic layered Intrusions and ultramafic flows and also may be important sources of PGEs. Such ores may also occur as podiform accumulations in plutonic sections of ancient obduction-related or Rift-related ophiolites.

Deposit Types	Principal Commodities	Critical Minerals/*Potential CMs*
Chromite	Cr	Cr
Sulfide	Ni, Co, Cu, PGE, Ag, Au, Se, Te	Co, PGE, Te
PGE	PGE	PGE
Fe-Ti	Fe, Ti, V, P	Ti, V, REE

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